THE STRUCTURE OF THE BULLER TERRANE WEST OF THE ANATOKI THRUST, UPPER COBB VALLEY, NORTHWEST NELSON, NEW ZEALAND.

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Frontispiece: View looking to the east over the study area from Mt Gibb to Waingaro Peak. Fenella Hut can be seen in the valley floor.

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ABSTRACT

The Buller terrane west of the Anatoki Thrust in the upper Cobb Valley area is composed of Ordovician marine sediments. Rocks in the field area are divided into two domains of different structural styles. In the west Domain 1 includes the Roaring Lion Formation which displays a series of mesoscopic gently plunging upright folds on the limb of a single megascopic fold. Folding is associated with low greenschist facies metamorphism. Domain 2 comprises rocks of the Aorangi Mine, Leslie, Douglas and Peel Formations; which contain three cleavage sets. The last cleavage is associated with a reclined fold in the east of Domain 2, which is correlated with folding at Gouland Downs to the north.

Domain one was brought into contact with Domain two by thrusting and strike slip movement along the Fenella Fault Zone, a steeply dipping zone of bedding concordant faulting.

Geochemistry shows the Roaring Lion Formation is very similar to the Greenland Group of Westland, the small differences shown by the Roaring Lion Formation are because it is slightly richer in quartz.

Analysis of calcite fabrics from deformed Mount Patriarch Formation limestone which occurs as a fault sliver in the Anatoki Thrust Zone, indicates the last movement on the Anatoki "Thrust" was normal.

CHAPTER ONE

INTRODUCTION

REGIONAL GEOLOGY

In Northwest Nelson, Lower Paleozoic rocks can be divided into three sedimentary belts; Western, Central, and Eastern. The Western Belt is part of the Buller terrane, and the Central and Eastern Belts lie within the Takaka terrane. The two terranes are separated by the Anatoki Thrust, a major fracture which is seen to extend from the Alpine Fault near Springs Junction, to the coast north of Aorangi Mine (Fig.1).

The oldest rocks within the Buller terrane are the Greenland Group of Westland, the Webb Formation of Aorangi Mine, and the Roaring Lion Formation of Northwest Nelson. They are quartz rich turbidite sequences, and spatially the most important units within the Buller terrane. However fossils are very scarce. The Greenland Group contains a single fossil locality bearing Lower Ordovician graptolites (Cooper, 1974).

At Aorangi Mine the Webb Formation is overlain by the Aorangi Mine Formation, a sequence of quartzites and graptolitic black slates of Lancefieldian to Yapeenian ages. This is in turn is overlain by a series of Darriwilian sandstones, mudstones and slates making up the Slaty Creek Formation. The conformable Ordovician sequence ends with laminated siltstones, quartz sandstones and mudstones named Formation A (Cooper, 1979b).

The Ordovician rocks seen in the Cobb Valley area can be correlated with those of the Aorangi Mine area: The Leslie Formation is equivalent to the Slaty Creek Formation; and

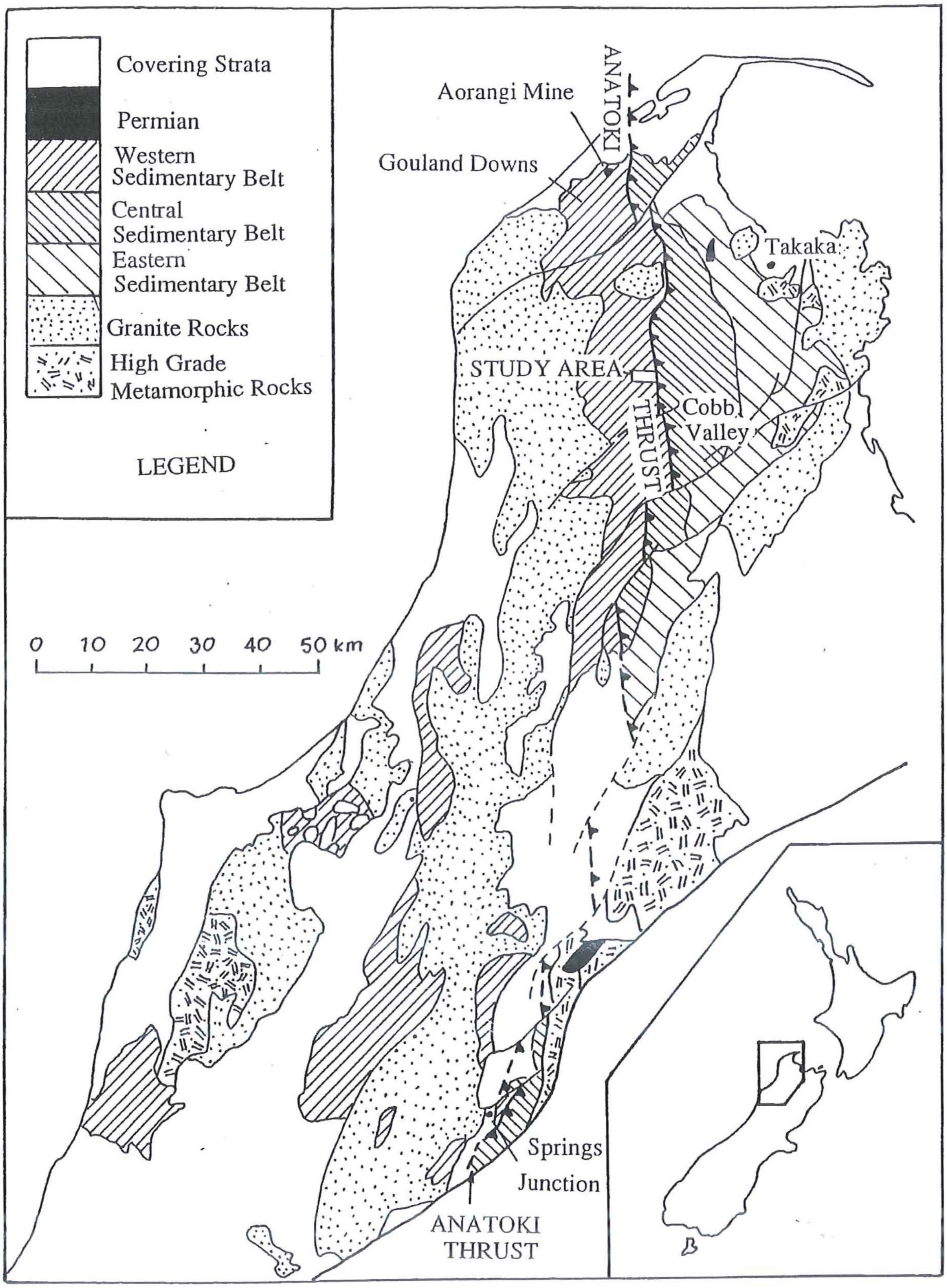


Fig. 1. Simplified geological basement map of Northwest Nelson and Westland. (After Cooper, 1989).

the Douglas and Peel Formations correlate with Formation A (Fig.2). The Aorangi Mine Formation in the Cobb Valley has been tectonically truncated by the Fenella Fault Zone, so only a remnant of the full sequence remains (Cooper, 1989 and Cooper and Tullock, 1992). Before the Fenella Fault Zone was recognised by Cooper (1989), the slates and quartzites of the Aorangi Mine Formation were mapped conformably below the Leslie Formation (eg Grindley, 1980).

AIMS

The objectives of this thesis are threefold. Firstly to analyse the structure of the Buller terrane in the field area. In particular to assess the internal structure of the Fenella Fault Zone. Secondly to make a comparison of the Roaring Lion Formation with the Greenland Group, and to assess the extent of their similarities. Finally, to determine a sense of movement for the Anatoki Thrust by analysing rocks at the Buller - Takaka terrane boundary.

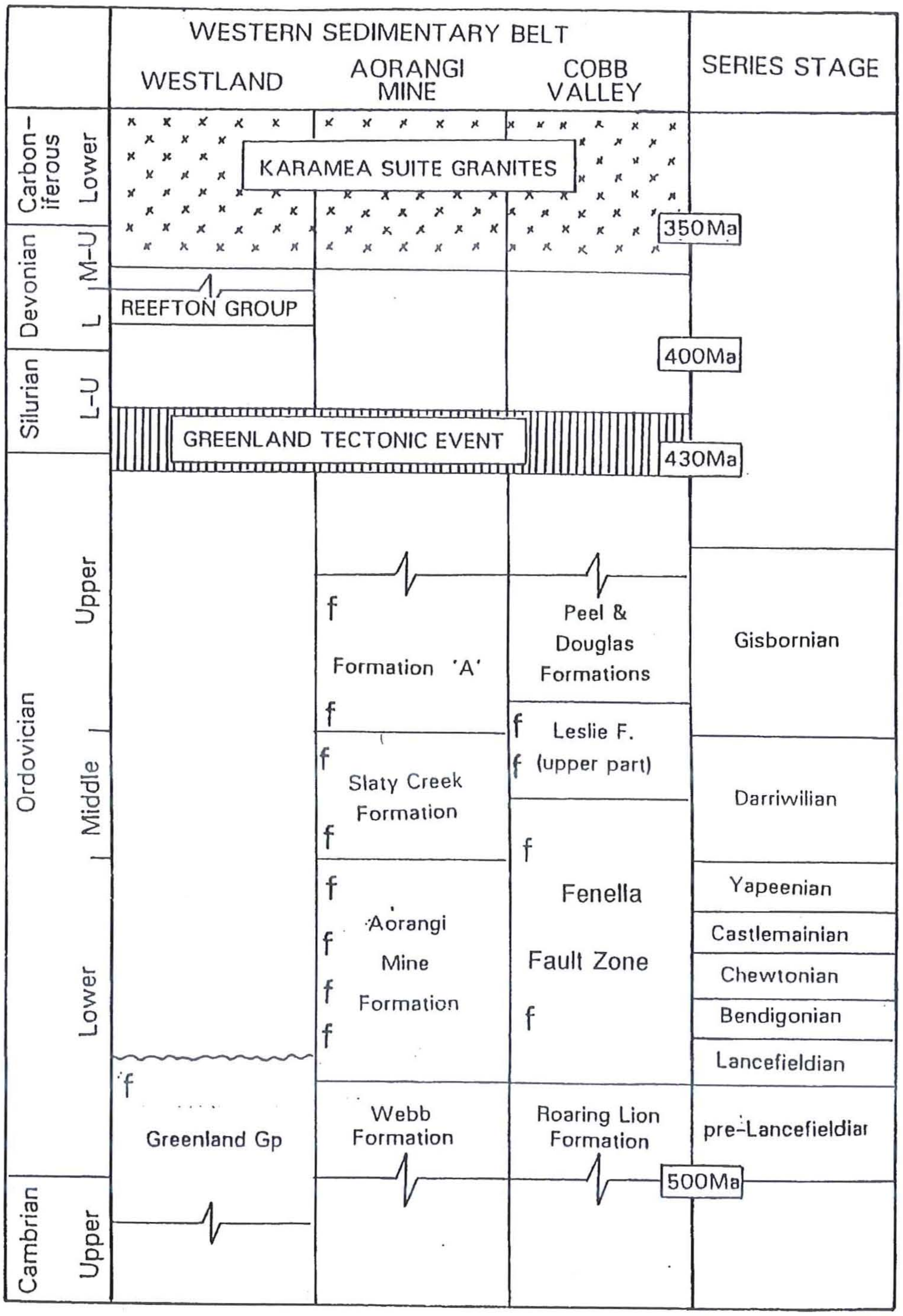


Fig.2. Buller terrane sedimentary units, igneous and tectonic events. f=age diagnostic fossil. (After Cooper, 1989).

STUDY AREA

The study area occupies about 25 km^2, centred around the upper Cobb Valley, Northwest Nelson (Fig. 3)

Vehicular access to the Cobb Valley is provided by the Cobb Hydro Road which runs to the Cobb Reservoir from Upper Takaka. A foot track follows the valley floor from the reservoir to the thesis area. Other foot tracks provide access to the ridges above Cobb Valley, with the remaining area passable by ridge tops, streams or untracked forest. Two Department of Conservation huts, Cobb Hut and Fenella Hut, were used as field bases.

Topography is rugged, having mainly been formed by glaciation in the Pleistocene. Most of the valleys still display the characteristic U profile, and cirques such as Round Lake are also commonplace. Xenicus Peak is the most impressive feature of the area, with two vertical cliff faces of over 100 metres. However Kakapo Peak on the eastern boundary of the field area is the highest, at an elevation of 1783m. The field area includes the watersheds between Burgoo Stream, the Roaring Lion, Cobb, and Waingaro Rivers.

Vegetation is *Nothofagus* / *Podocarpus* forest. It is dense, and extends from the valley floors up to the treeline of about 1400m. Above this elevation sub-alpine tussock predominates, although some glaciated rocks remain bare providing excellent outcrop. Outcrop in the bush is very poor.

Snow makes fieldwork impossible from May to September, covering both the ridge tops and upper reaches of the surrounding valleys. Snow fall was particularly heavy in 1992.

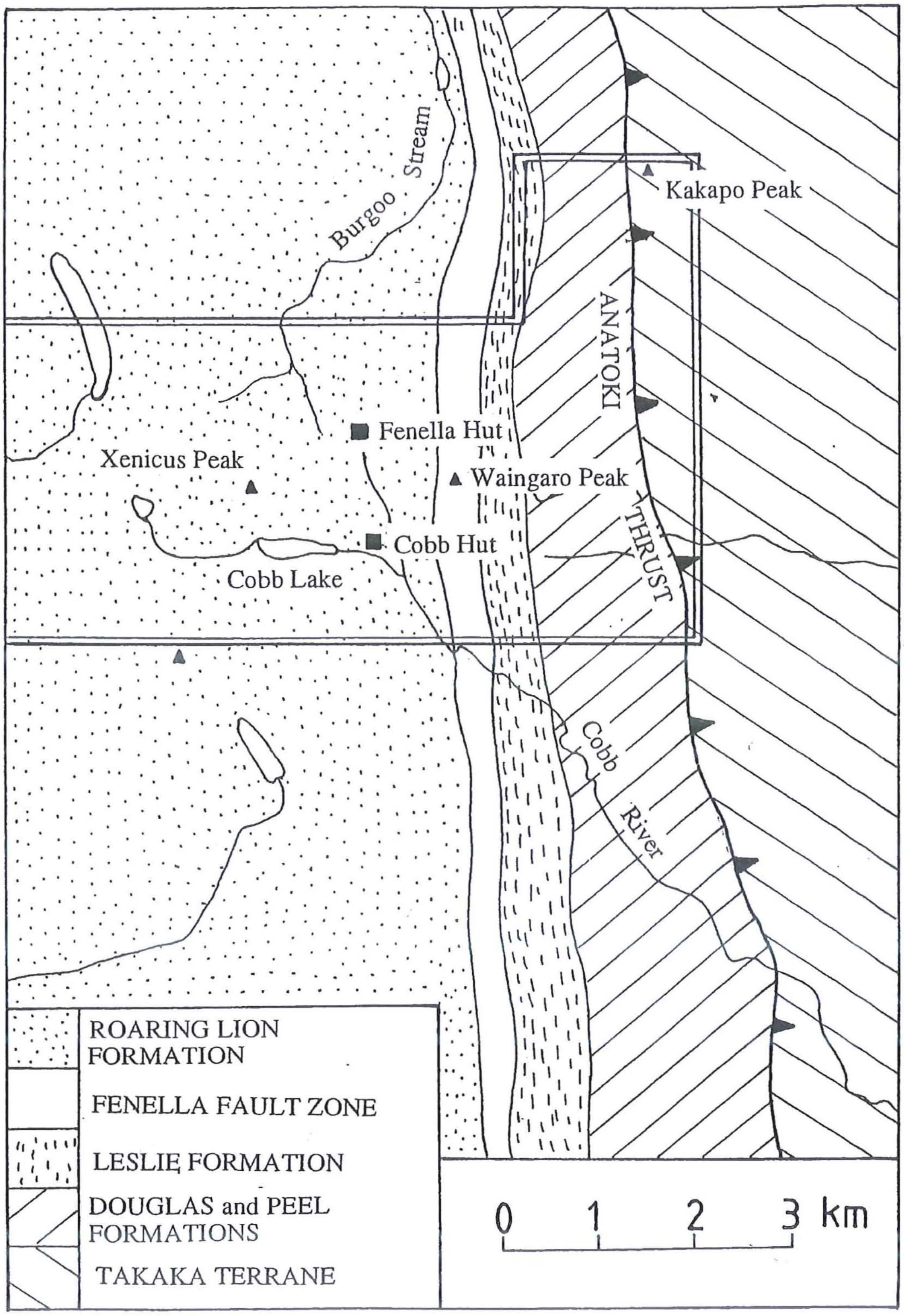


Fig.3. Simplified geological map of the study area (outlined by double border).

MAPPING AND METHODS

Mapping was undertaken from January '92 to January '93, for a total of 7 weeks spent in the field. Airphoto runs SN 8409 N/15, O/15-17, and P/11-13 were used to map on in the field, and this data was transferred to a basemap enlarged to 1:10000 from Cobb Sheet, NZMS 260 M26.

Thin sections for microscopic analysis were made using Logitech equipment.

Geochemical samples for XRF analysis at the University of Canterbury were prepared by firstly crushing and grinding the samples to a fine powder. Pressed 50mm diameter pellets for XRF trace element analysis were then made using a solution of 7% aqueous polyvinyl alcohol. Fusion beads for XRF major element oxide analysis were made following the standard methods of Norrish and Hutton (1969).

Structural data were plotted using a Rockware software package.

CHAPTER TWO

REVIEW

INTRODUCTION

Northwest Nelson has been investigated by geologists since the later part of last century. The geological complexity of the area is such that many questions remain unanswered despite numerous reports since this time. This chapter reviews published work dealing with the regional structure of Northwest Nelson.

BACKGROUND

McKay (1879) was the first geologist to formally subdivide the rocks of Northwest Nelson. He named the Mount Arthur Series and assigned a Lower Silurian age[1]. He also described what he considered to be Upper Devonian rocks in the Arthur Range - Mount Peel area (now known to be Cambrian) which Cox correlated with the Te Anau Series in 1882. Bell *et al.* (1907) renamed the Te Anau Series in Northwest Nelson the Haupiri Series, "*...a new name of no definite age significance.*" Finally the Aorere Series was named by Hector in 1886. Keble and Benson (1929) documented Middle to early Late Ordovician graptolites from the Aorere Series in Cobb Valley. The term 'Series' has since been replaced by 'Group'.

[1] Hector and Cox used the Murchison or Continental classification. Silurian is equivalent to the Ordovician of today.

Cooper revised the terminology and equated the Aorere, Haupiri and Mount Arthur Groups with the Western, Central, and Eastern Sedimentary Belts respectively (1979, p36). The Western Sedimentary Belt is also equivalent to the Buller terrane, and the Central and Eastern Sedimentary Belts are equivalent to the Takaka terrane.

REGIONAL STRUCTURE

Structural models of Northwest Nelson developed as the stratigraphy of the region became better understood. Park thought the Aorere Series was folded into a syncline containing the Te Anau Series "*In the synclinal fold of the Silurian rocks which extends from the Aorere Valley southward to Mount Arthur, there is included a great thickness of green and red slates, graywackes, and slaty breccias of Devonian age, forming the higher and bolder portions of the Haupiri, Anatoki, and Waingaro Ranges, including also Mount Snowdon and Mount Peel.*" (1890, p201).

The essence of this model remained unchanged until Benson (1956) found the Haupiri Series to be Cambrian. This was a major revelation. It established that the Ordovician Aorere Series was younger than the structurally higher Haupiri Series. A more complex model was needed to explain the structural history.

THE ALLOCHTHONOUS CENTRAL BELT HYPOTHESIS

Grindley (1961) proposed that the Haupiri Group comprised three nappes thrust northward over an autochthonous basement of Mt Arthur and Aorere Groups. The nappes were subsequently folded into a synform trending approximately north to create the structure present today. Supporting evidence has been presented by Grindley over the last twenty years and can be briefly summarised as:

1) Closing of the basal (Anatoki and Devil River) thrust to the north.

2) The presence of tectonic windows within the Haupiri Group exposing younger Haupiri rocks below. For example Grindley (1980) maps the younger Cambrian Anatoki Formation and Waingaro Schist below the older Cambrian Devil River volcanics, Tasman and Locket Formations in Waingaro Valley.

3) Varied structural evidence within the Haupiri Group including northward verging recumbent folds and deformed conglomerate pebble lineations indicating a northward transport direction.

4) "Reclined recumbent" folds in the underlying Mt Arthur and Aorere Groups below the basal thrust.

5) The recognition of an inverted sequence of discrete nappes.

This "evidence" has been the subject of debate . The area involved is large and stratigraphic and structural control is poor. As a result the evidence of the Devil River fault and Anatoki Thrust closing to the north, the identification of nappes, and the inverted stratigraphy etc. are only inferences. The meaning of structures within the Haupiri Group is also unclear, and thrusting from the south is questionable. Cooper (1979a, 1989) and Bradshaw (1982) suggest thrusting from the east is a distinct possibility.

The gravitational sliding mechanism to emplace the Central Belt as outlined by Grindley (1971) was questioned by Powell who provided evidence suggesting that the "*...shear stress at the Devil River Thrust during metamorphism and deformation to have been unrelieved (or at least non-transient), and of considerable magnitude. The minimum estimate (35MPa) is well in excess of the maximum basal shear stress (10MPa) likely to be generated by gravity induced movement.*" (1984, p112).

Furthermore Grindley's belief that the Western and Eastern Sedimentary Belts: "*...may be contiguous parts of a single sedimentary basin.*" (1982, p376) is difficult to accept, especially as the two belts retain strongly contrasted stratigraphy even when only a few kilometres apart.

The reader is referred to Bradshaw (1982), Grindley (1982), and Cooper (1979 and 1989) for a more thorough discussion of the Allochthonous Central Belt model.

RECENT MODELS

Cooper (1979a) postulated that the Central Belt was thrust from under the Eastern Belt during the Late Ordovician to Early Devonian. In this model the Eastern Sedimentary Belt would have been down-thrust, resulting in the deposition of sediment derived from the older up-thrust Central Belt to the west, accounting for the similarities between Central and Eastern Belt lithologies. This model requires the Anatoki Thrust and Devil River Fault to originally have been east dipping thrusts.

More recently the Takaka and Buller terranes have been linked with the Lachlan Fold Belt of Australia (Cooper and Grindley, 1982 and Cooper and Tullock, 1992). Cooper and Tullock summarise "*The Buller terrane...is likely to have lain along the edge of the Australian-Antarctic segment of Gondwana...in Cambro-Ordovician time.*" They continue "*The Takaka terrane is interpreted as forming on or adjacent to a Cambrian island arc.*" and "*...was sutured on to the Gondwana margin, probably in the earliest Devonian but possibly not until after the Early Carboniferous.*" (1992, p141).

A better understanding of the geologic history of the region will only come with more stratigraphic and structural control. To define the structure is to define the stratigraphy, and vice versa. The two fields must be brought together if any general conclusions are to be made.

CHAPTER THREE

ROCK FORMATIONS

ROARING LION FORMATION

The Roaring Lion formation consists of a monotonous series of alternating slabby grey-green well indurated sandstone and indurated mudstone beds. The type section nominated by Grindley (1971) occurs in the field area between the headwaters of the Roaring Lion and Cobb Rivers.

PRIMARY SEDIMENTARY STRUCTURES

Bedding

Bed thicknesses range from 10 centimetres to 10 metres, with the great majority lying in the range of 20 centimetres to 5 metres. Generally sandstone beds are thicker than mudstone beds, and as a result make up the majority of the Roaring Lion Formation. Mudstone beds commonly comprise sets of laminated to thinly laminated beds (classification of Lewis, 1984). Both upper and lower contacts between sandstone and mudstone beds are sharp. Grading within beds is not well developed , but when seen it is normal, fining upwards (facing directions are provided by sedimentary structures described below). Bouma sequences are absent.

Bedding planes are very persistent and have been traced for distances of up to 250 m with no deviation before exposure is lost. Bedding is highly regular and is only compromised on a smaller scale by secondary sedimentary structures.

Cross Bedding

Only one set of cross beds was seen in the field area. The set was developed in a sandstone bed near the eastern margin of the Roaring Lion Formation, and exposed in an end section of bedding. Thinly laminated bedding sets comprised small trough structures of 2 cm across on average. Cross beds do not conclusively indicate a paleocurrent direction.

SECONDARY SEDIMENTARY STRUCTURES

Load and Flame Structures

Load structures are the most common sedimentary structures in the Roaring Lion Formation. They are simple dish shaped embayments of mudstone in sandstone, at bedding contacts and do not exceed 50 cm across.

Flame structures are well developed when they occur. Without exception mudstone intrudes into sandstone from an underlying bed (Fig.4). Flames of up to 60 cm high are developed in places. They provide reliable facing directions.

Slump Structures

Slump structures occurring in thinly laminated mudstone beds are very well developed in an area east of Round Lake (Fig.5). Here slumping is seen in sections perpendicular to

Fig.4. Flame structure in the Roaring Lion Formation. The mudstone bed at the bottom of the photograph embays a sandstone bed above. Pencil for scale=15cm.

Fig.5. Slumped bedding in the Roaring Lion Formation. Line drawing illustrates the position of sliding planes which dip to the south. Pencil for scale=15cm.

the dip of bedding. Slumped bedding sets are separated by small sliding planes on which slumping occurred. These sliding planes are spaced 15cm apart on average and cut bedding at an angle of 30^0. Sliding planes consistently dip to the south indicating a paleohigh to the north.

TEXTURE AND COMPOSITION OF SANDSTONES

Roaring Lion Formation sandstones in outcrop are coarse to fine moderately sorted arenites.

The essential mineralogy is quartz, muscovite, albite, chlorite, oxidised iron bearing minerals and opaques. Quartz grains comprise approximately 25% of the Roaring Lion Formation sandstones, and albite grains represent about 2% as do rock fragments. (Appendix One).

Albite is metamorphic in origin having grown in situ. Twinned grains are relatively uncommon and are probably detrital in origin. Quartz is largely monocrystalline with some polycrystalline quartz from either a high temperature metamorphic or igneous source (Fig.6). Rock fragments are dominated by high temperature quartz and feldspar aggregates and also represent a high grade metamorphic or igneous source.

The remaining 70% of the rock is composed of matrix or apparent matrix. Of this 70%, approximately 50% is quartz with the remaining 20% largely muscovite with minor chlorite and albite (Fig.7). It is difficult to accurately determine the proportion of matrix quartz and feldspar due to the fine grained nature of the matrix. The matrix represents mudstone clasts, silt and feldspars which were altered and recrystallised during metamorphism.

The Roaring Lion Formation plots in the Subfeldsarenite to Sublitharenite fields of Folk *et al.* (1970) (Fig.8).

Textures within the Roaring Lion Formation have been strongly influenced by metamorphism. Quartz grains have a moderate shape preferred orientation elongate parallel to cleavage. The origin of the S.P.O. is pressure solutioning of quartz grains and redeposition in strain shadows beside grains. Cleavage is defined by anastomosing muscovite layers which wrap around grains. Beards of muscovite are also present (Fig.9).

The metamorphic texture of the Roaring Lion Formation conforms to the characteristics of the Chlorite 2 subzone of Turner (1935) or Textural Zone 2a of Bishop (1972). They are slightly foliated with a faint micaceous sheen on foliation surfaces.

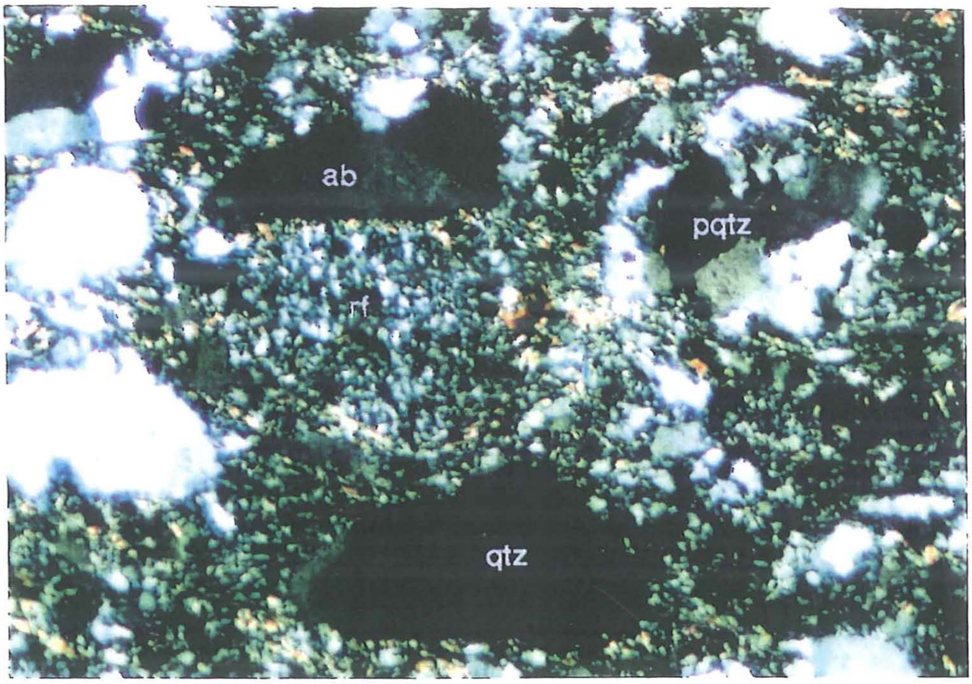


Fig.6. Monocrystalline and polycrystalline quartz in the Roaring Lion Formation. (Sample RLF6). pqtz=polycrystalline quartz, qtz=quartz, ab=albite and rf=rock fragment. Mag.x16 Crossed polars.

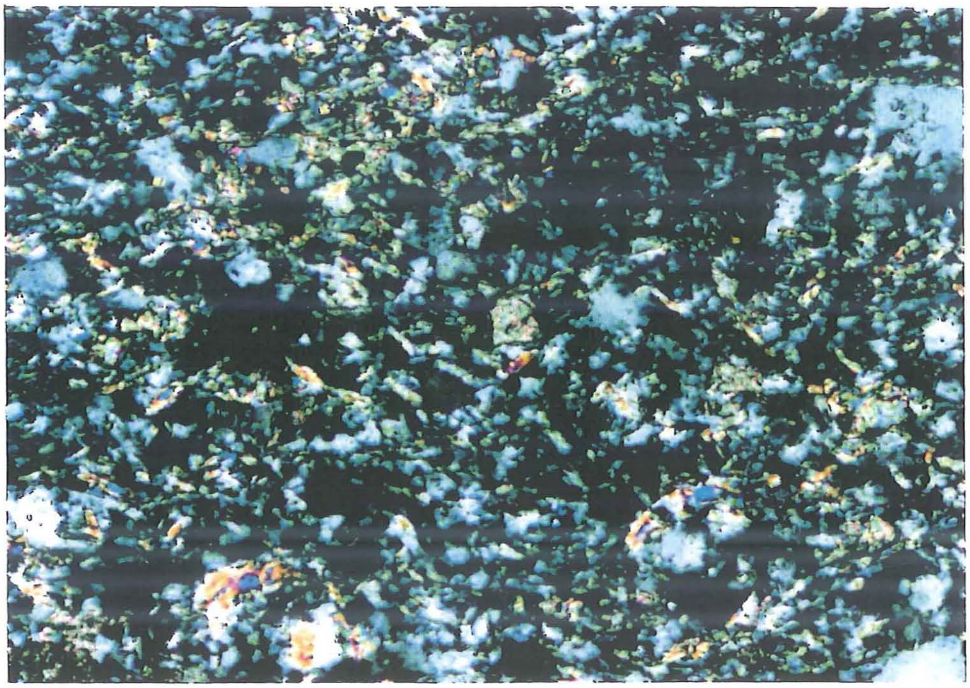


Fig.7. Metamorphic matrix of the Roaring Lion Formation which comprises quartz, albite and muscovite. (Sample RLF2). Mag.x10 Crossed polars.

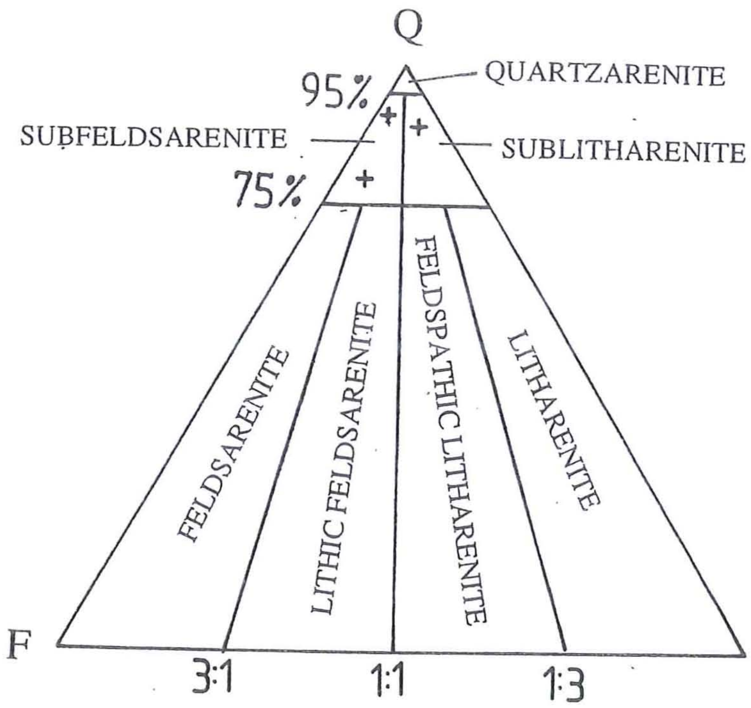


Fig.8. Parent triangle for arenite classification. +=Roaring Lion Formation (Appendix One). Q=monocrystalline and polycrystalline quartz, F=feldspar, and R=rock fragments. (After Folk *et. al*, 1970).

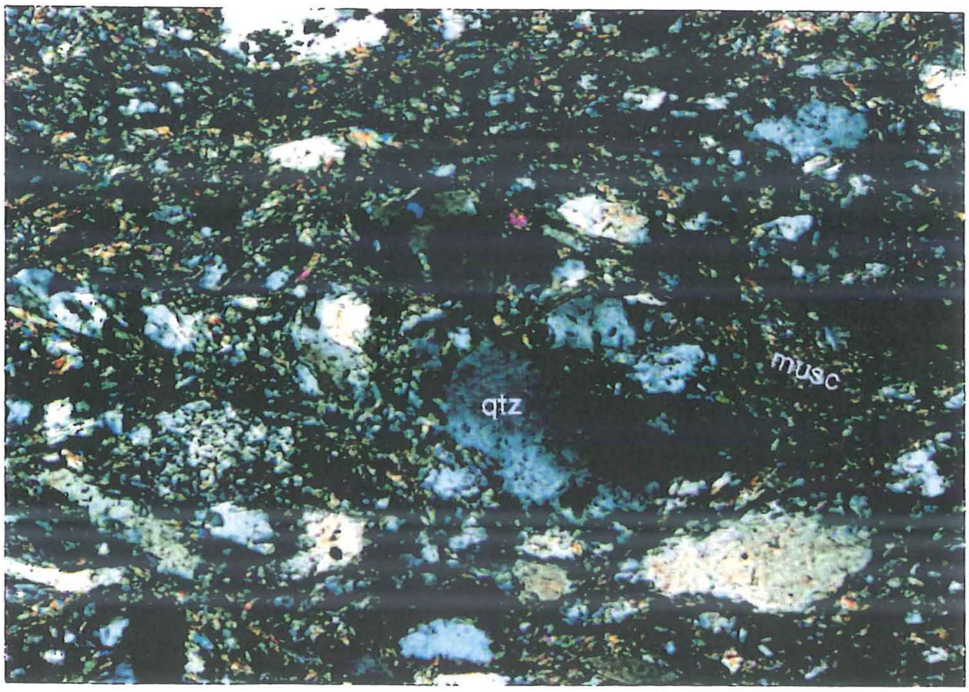


Fig.9. Pressure solutioning of quartz has created a shape preferred orientation. Layers of muscovite wrap around quartz grains. (Sample RLF7). qtz=quartz, musc=muscovite. Mag.x40 Crossed polars.

The mineralogy suggests metamorphism peaked at the chlorite zone of the greenschist facies (lower greenschist facies). The absence of biotite indicates pressure-temperature conditions did not reach the middle greenschist facies. Zeolites, prehnite, pumpellyite and lawsonite are also absent indicating metamorphism exceeded the low pressure-temperature Prehnite-pumpellyite and Lawsonite-actinolite facies.

DEPOSITIONAL SETTING

A low energy environment forming a monotonous, laterally continuous, regular, thick and extensive set of beds suggests the Roaring Lion Formation is a deep water deposit of an extensive marine basin. The unfossiliferous nature of the Roaring Lion Formation also indicates it was probably deposited in an off-shelf environment. Slump structures and rare graded beds are consistent with lower flow regime currents, probably turbidity currents, periodically bringing sand into the basin. Grindley (1980) also interprets the Roaring Lion Formation to have been a turbidite deposit.

THE GOLDEN BAY GROUP

THE AORANGI MINE FORMATION

The name Aorangi Mine Formation is used here for slates and quartzites contained within the Fenella Fault Zone. Previously they have been mapped as the lower part of the Leslie Formation (eg Grindley, 1980). However Cooper (1989) believes the Fenella Fault Zone has tectonically thinned Aorangi Mine and possibly lower Slaty Creek Formations. Cooper (1989) renamed the rocks within the Fenella Fault Zone the "Leslie Quartzites" after the distinctive quartzite beds which they contain. Later Cooper and Tullock (1992) mapped these rocks as the Aorangi Mine Formation.

Grindley (1961) proposed the name Aorangi Mine Formation for "*...dark graphitic argillites and interbedded quartzites. At Aorangi Mine and Slaty Creek the argillites contain Lower Ordovician (Arenigian) graptolite faunas...*". Later Bishop (1968) nominated the type section which is in the Aorangi Mine area some 40 kilometres north of the field area, the most detailed description of which is by Cooper (1979b). Cooper subdivided the Formation into four units (listed oldest to youngest):

Malone Member (Lancefieldian): Thick-bedded and massive, pale, quartz rich sandstone and rare interbedded pale siltstone and black shale.

Anthill Black Shale (Castlemainian-Lancefieldian): Siliceous black shale and chert with sandstone bands.

Battery Member (Yapeenian-Castlemainian): Soft massive siltstone with interbedded bands of hard quartz sandstone and black slate.

Jimmy Creek Quartzite (Yapeenian): Two thick quartzite units and an intervening band of interbedded sandstone and micaceous siltstone (Table 1).

The Aorangi Mine Formation is approximately 1000 metres thick at its type section.

Extension of the Aorangi Mine Formation to the Cobb Valley is justified by lithological and chronological similarities.

Cooper (1989) reported Bendigonian graptolites from within the Fenella Fault Zone. At Aorangi Mine the Anthill Black Shale of the Aorangi Mine Formation also contains Bendigonian graptolites (Cooper, 1979b). This is significantly older than the Upper Darriwilian graptolites from the Leslie Formation documented by Skwarko (1962).

Lithologically the rocks contained within the Fenella Fault Zone are similar to those at Aorangi Mine, although they are tectonically thinned and only represent a thickness of 100 m, a fraction of the full Aorangi Mine Formation.

In the field area the formation is marked by two distinctive quartzite beds separated by black graphitic slates.

QUARTZITES

The quartzite beds average a thickness of 10 m, dip vertically, and are extremely resistant to weathering. They stand out prominently from the surrounding slates and can be traced on air photos from Boulder Lake to the Mount Patriarch area (Fig.10). They are massive, well indurated and white in colour.

LITHOSTRATIGRAPHIC UNIT		AGE		
Formation A		Gisbornian-Darriwilian	UPPER	ORDOVICIAN
Member 3	SLATY CREEK FORMATION	Darriwilian	MIDDLE	
Member 2				
Member 1				
Jimmy Creek Quartzite	AORANGI MINE FORMATION	Yapeenian	LOWER	
Battery Member		Yapeenian-Castlemainian		
Anthill Black Shale		Castlemainian-Lancefieldian		
Malone Member		Lancefieldian		
Webb Formation		Lancefieldian-Cambrian?		

Table 1. Sedimentary units at Aorangi Mine and their graptolite stages. (After Cooper, 1979b).

Quartz grains comprise in excess of 95% of the rock. The remaining 5% is largely chert which occurs as either rock fragments or in veins. Oxidised iron bearing minerals, rock fragments and muscovite together account for less than 1% of the rock.

Rock fragments are predominantly composed of chert and are not genetically linked with vein chert (Fig.11). Fragments of either high temperature metamorphic or igneous rocks are extremely rare (Fig.12).

The quartzites are well sorted with grain sizes from coarse sand to fine sand. A matrix is absent. Grains are Sub-rounded to Sub-angular.

The most interesting feature of the quartzites are small veins infilled with chert. The veins are spaced 50mm apart on average and have a maximum width of 5mm. They can only be seen in thin section, and it is not known if they are uniformly oriented throughout the quartzites. Vein boundaries are very sharp indicating microfracturing opened the voids which were infilled by chert deposited from fluids. Small quartz grains also occur within the veins, representing crushed fragments produced by the microfracturing. These quartz fragments were aligned in bands parallel to the vein walls by the fluids which deposited the chert (Fig.13). Incipient replacement of quartz by chert can also be seen in weakly developed and slightly anastomosing veins running off the more persistent veins.

The quartzites plot in the quartzarenite field of Folk *et al.* (1970).

Apart from vein formation the original sedimentary petrology has not been altered to any large degree. Grain boundaries are dusty, a characteristic of unaltered sedimentary

Fig.10. Quartzite band running down the back of Waingaro Peak looking to the southwest.

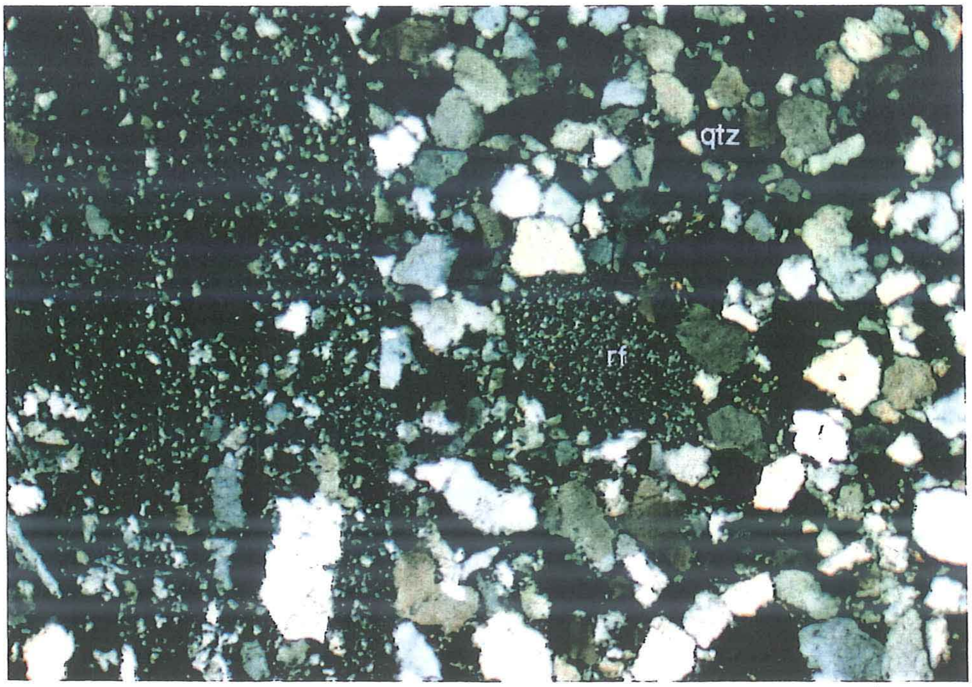


Fig.11. Chert occurs as rock fragments and in veins within the quartzites of the Aorangi Mine Formation. (Sample LQ3c). qtz=quartz, rf=rock fragment. Mag.x40 Crossed polars.

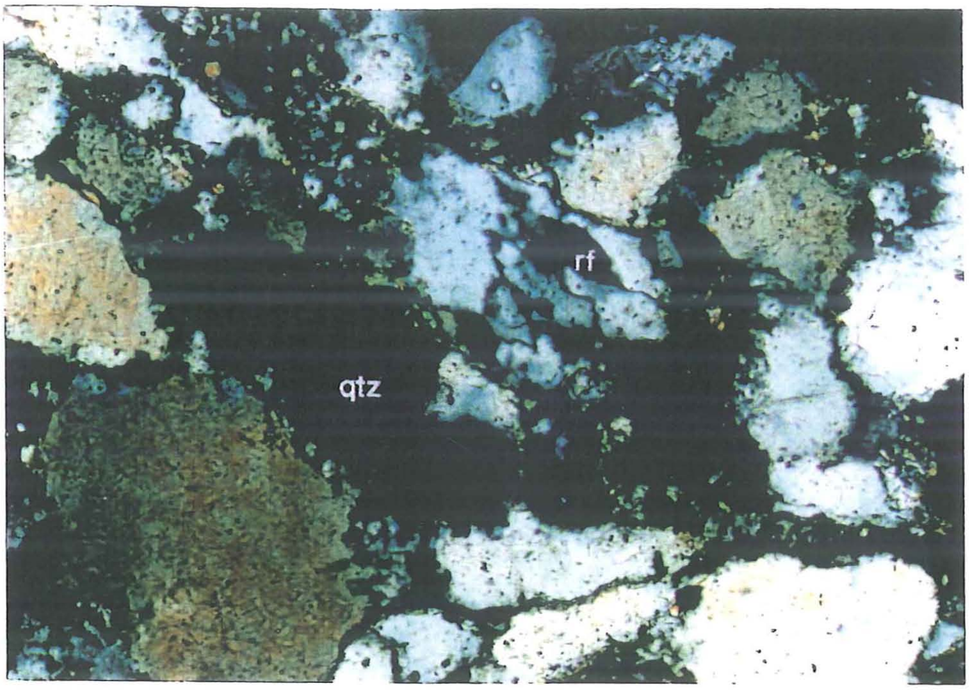


Fig.12. Fragment of a high temperature metamorphic or igneous rock within a quartzite of the Aorangi Mine Formation. (Sample LQ3c). qtz=quartz, rf=rock fragment. Mag.x40 Crossed polars.

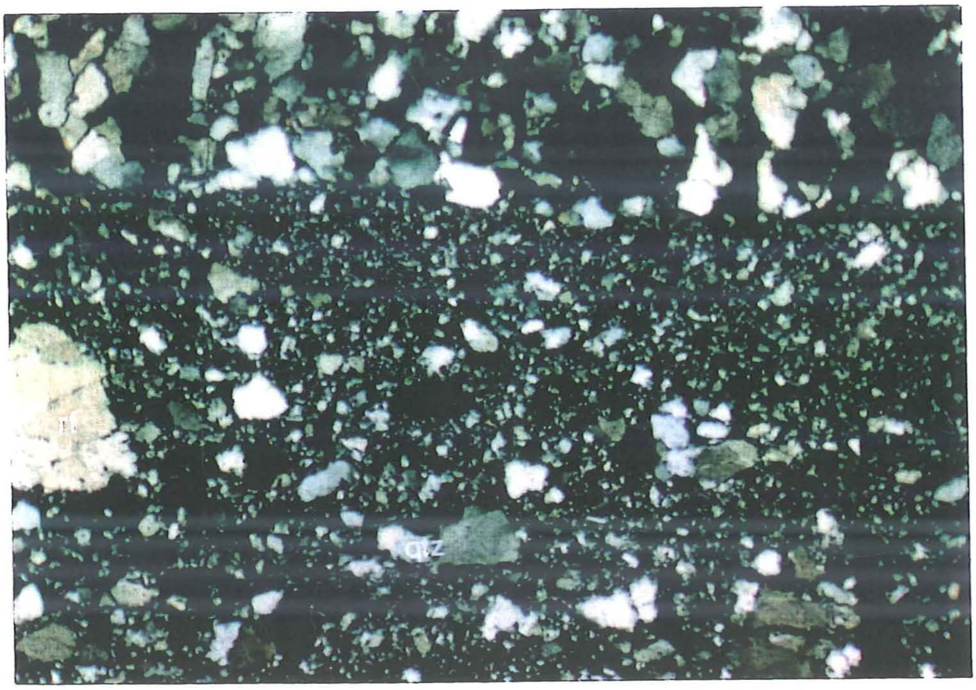


Fig.13.Chert vein containing fragments of quartz aligned parallel to vein walls. (Sample LQ3c). qtz=quartz, rf=rock fragment. Mag.x40 Crossed polars.

quartzites (Shelley, 1992). No shape or lattice preferred orientations are present. However quartz grains display undulose extinction indicating they have been subjected to some strain since deposition.

SLATES

Previously these rocks have been called slates (Skwarko, 1962), argillites (Grindley, 1980) and shales (Cooper, 1989). Here the classification of Potter *et al.* (1980) is used which classifies 'shales' with a "*...cleavage that is independent of original sedimentary structures.* " (1980, p17) as slates. Slates of the Aorangi Mine Formation have a very well developed cleavage. They are well indurated and black in colour. Recrystallised minerals are aligned parallel to the well developed cleavage.

The slates are composed of laminations of sericite, graphite, pyrite and minor amounts of quartz. It is not possible to determine the exact proportions of the components because of the fine grained nature of the rock. Grains are very fine silt to clay in size.

Lithologically the Malone Member, Anthill Black Shale, and Battery Member could all be correlatives of the slates, and the Jimmy Creek Quartzite a correlative of the quartzites within the field area. More fossil evidence is required to provide a well constrained correlation of the rocks within the Fenella Fault Zone with those at Aorangi Mine. However they are the same age, of the same sedimentary character and they occur along strike from the rocks at Aorangi Mine. These facts justify the correlation between the Cobb Valley and Aorangi Mine.

THE LESLIE FORMATION

The western edge of the Leslie Formation is in fault contact with the Aorangi Mine Formation, but the eastern margin passes conformably into the Douglas Formation. The Leslie Formation is made up of black slates and minor quartzites. The type section nominated by Grindley (1961) is in the field area between the Cobb and Burgoo Rivers and includes the rocks mapped here as the Aorangi Mine Formation. The Leslie Formation is 1050m thick in the field area. The Leslie Formation here is equivalent to the Leslie Formation (upper part) of Cooper (1989).

SLATES

Apart from fossil content the slates are indistinguishable from those of the Leslie Quartzites (Fig.14). Graptolites are abundant and well documented by Keble and Benson (1929); and Skwarko (1960) who notes "*The richness of the fauna increases until...it reaches the acme of development which is truly spectacular.*" (1960, p6). Graptolites of Upper Darriwilian to Lower Gisbornian ages are represented.

QUARTZITES

Minor quartzarenite beds of up to 5 metres thick occur in the Leslie Formation. They are white in colour and well indurated. Petrographically they are distinct from the Aorangi Mine Formation quartzites: Chert is absent, and plagioclase is present (albeit in very small amounts). Very minor amounts of muscovite are also present. The texture also differs from that of the Aorangi Mine Formation. The quartzites are clast supported well sorted bimodal rocks. The two mode grain sizes being very fine sand and fine silt (finer than the Aorangi Mine Formation). Grains are angular.

THE DOUGLAS FORMATION

The Douglas Formation is a well cleaved grey subfeldsarenite; and its type section continues on from that of the Leslie Formation. It contains quartz, albite, muscovite, chlorite and iron weathering products (Fig. 15). Bedding is made of layers of coarse silt to fine sand sized grains. Bed thicknesses range from 2 mm to 5 cm, the majority being about 5 mm thick. The rock contains three cleavages, the dominant one is parallel to bedding and has been overprinted by two less well developed cleavages.

A lattice preferred orientation is present parallel to the first cleavage (see Chapter Four on origin of cleavage). The cleavages are defined by muscovite. The Douglas is Gisbornian in age (Grindley 1971).

THE PEEL FORMATION

The Peel Formation is very similar to the Douglas Formation. It is also a grey subfeldsarenite with the mineralogy being essentially the same: quartz, albite, muscovite and chlorite. Grain size is very fine sand (Fig.16).

The Peel Formation was first mapped by Grindley (1961) and later in 1971 he nominated the type section which continues on from that of the Douglas Formation to the Anatoki Thrust. In the field the two units are practically indistinguishable, and have been mapped together here. It is unclear why Grindley defined the Peel and Douglas as distinct

Fig.14. Leslie Formation. Slaty cleavage parallels bedding. For scale notebook is 17cm long.

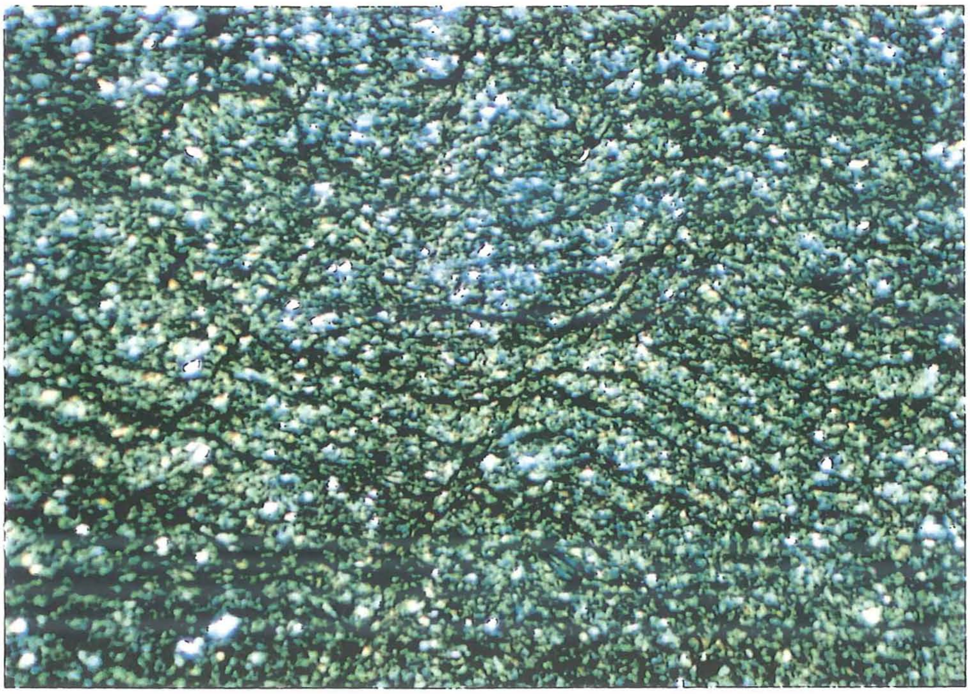


Fig.15. Douglas Formation composed of quartz and albite grains with cleavages defined by muscovite (also see Fig.30). (Sample KP3). Mag.x10 Crossed polars.

formations or whether they are viable mapping units.

DEFORMED LIMESTONE

Limestone occurs as a faulted sliver within the Anatoki Thrust Zone. It has been mapped by Grindley (1980) as Mount Patriarch Formation near Kakapo Peak. To the south it juts out from the Locket Range forming a large buttress, and is mapped as Summit Limestone.

At the microscopic scale zones of sheared calcite wrap around relatively undeformed calcite porphyroclasts. Crinoid ossicles and shell fragments are recognisable; indicating that the rock has not been totally recrystallised (Fig.17). The Mount Patriarch Formation is dated by trilobites as uppermost Cambrian to basal Ordovician (Grindley, 1980), with deformation occurring during movement on the Anatoki Thrust. Chapter Six provides an analysis of crystallographic preferred orientations.

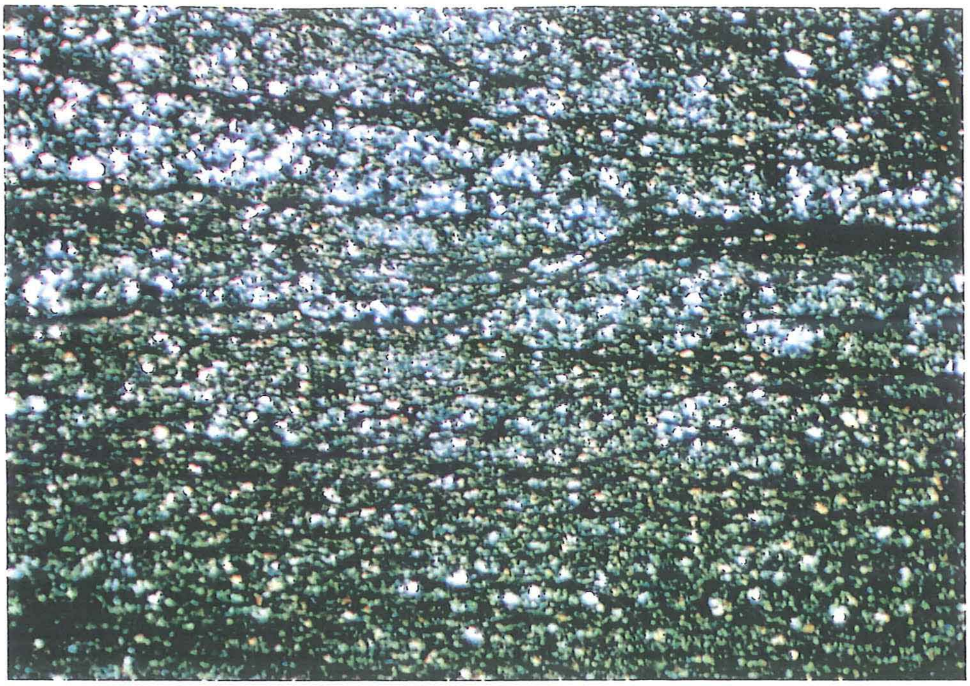


Fig.16. Peel Formation displaying a similar composition and texture to the Douglas Formation. Bedding contains quartz and albite; and runs across the field of view. (Sample KP7). Mag.x10 Crossed polars.

Fig.17. Crinoid ossicle in the deformed Mt. Patriarch Group. A tectonic foliation runs across the field of view. (Sample SL1). osc=ossicle. Mag.x10 Crossed polars.

CHAPTER FOUR

STRUCTURE

STRUCTURAL DOMAINS

The field area can be divided into two domains of differing structural styles: **Domain 1** is the Roaring Lion Formation and **Domain 2** covers the remainder of the field area - the Aorangi Mine, Leslie, Douglas and Peel Formations. The domains are separated by the steeply dipping north striking Fenella Fault Zone (FFZ).

Structures within each of the domains are described separately from oldest to youngest. A discussion of their interrelationship and the structural development of the region follows at the end of the chapter. The descriptive terminology follows Ramsay (1967).

DOMAIN ONE: The Roaring Lion Formation.

RLF_1: In the field area RLF_1 folding consists of mesoscopic folds on the limbs of a single megascopic fold. Spectacular arrays of mesoscopic folding are seen in the cliffs below Xenicus Peak and they are typical of the RLF_1 folding style throughout the field area (Fig.18). Fold attitudes are upright to steeply inclined and gently plunging (12^0 on average) to the south (Fig.19). Fold morphology is similar, asymmetric, with an average wavelength of 12 m. Tightness is close to open (Fig.20).

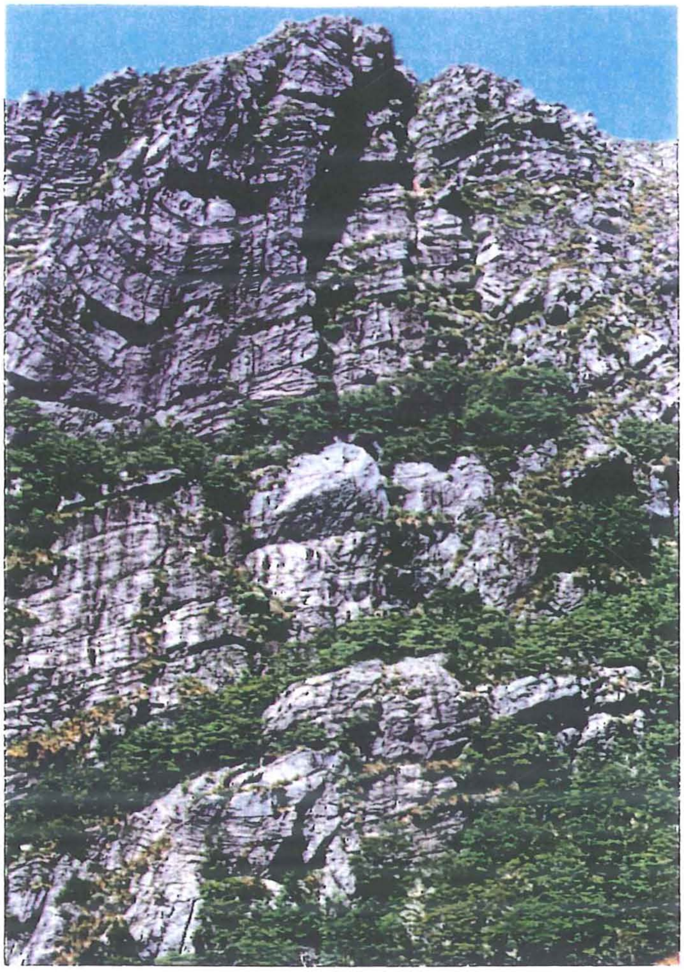


Fig. 18. RLF_1 folding in the north face of Xenicus peak. View measures approximately 50 metres across.

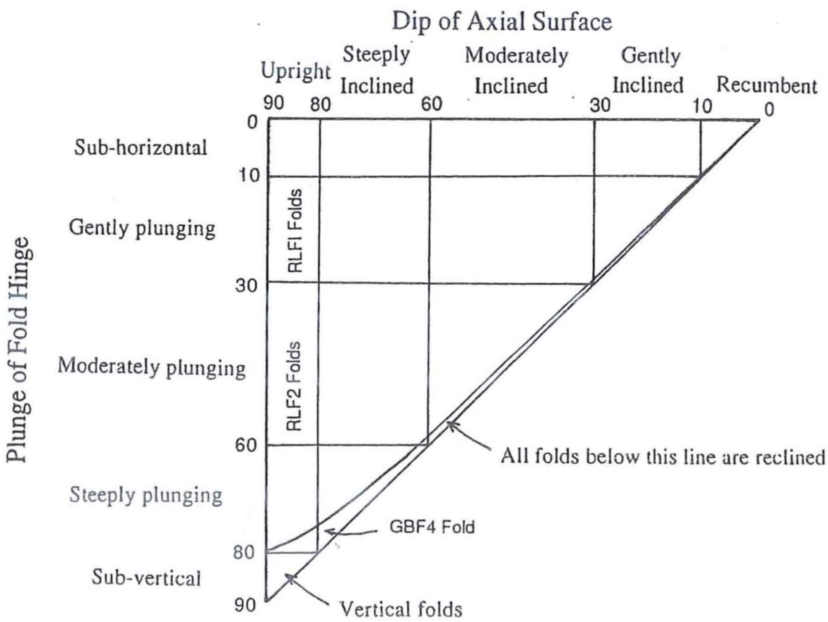


Fig. 19. Classification of folds within domains 1 and 2. (After Fleuty, 1964).

Mesoscopic folds climb up to the axis of the megascopic anticline in the west of the field area. This large fold is of a similar style to the mesoscopic folds except its western limb is overturned (Appendix 3: cross sections A-A'and B-B').

Bedding orientations illustrate the meridional trend of folding (Fig.21). A well developed slaty cleavage (RLS_1) is associated with RLF_1 folding and it fans about the megascopic fold. The average strike of the cleavage is close to that of bedding (Fig.22). Bedding cleavage intersection lineations (RLL_1) plunge at equally shallow angles to the NNW and SSE as is expected when bedding and cleavage have similar strikes (Fig.23).

Folding is associated with low greenschist facies metamorphism.

TIMING

RLF_1 corresponds to Grindley's (1978) second movement phase (F2) Tuhua Orogeny. In relation to the Allochthonous Central Belt model, 'F2' folded the sequence of central belt nappes into a synclinorium in addition to folding the Roaring Lion Formation. Grindley dated this event as Middle Devonian "*...following deposition of the Lower Devonian beds at Reefton and Baton River, and preceding emplacement of the Upper Devonian to Lower Carboniferous Karamea Batholith.*" (1978, p127).

RLF_1 also conforms with the following description by Cooper and Tullock (1992) of folds produced by the Greenland Tectonic Event "*The Greenland Tectonic Event produced folds throughout the* (Buller) *terrane with a WNW-NNE axial trend and steep axial planes, a well developed cleavage and low grade (low greenschist facies) metamorphism.*" (1992, p139). Cooper (1979a, 1989) and Cooper and Tullock (1992) date the Greenland Tectonic Event

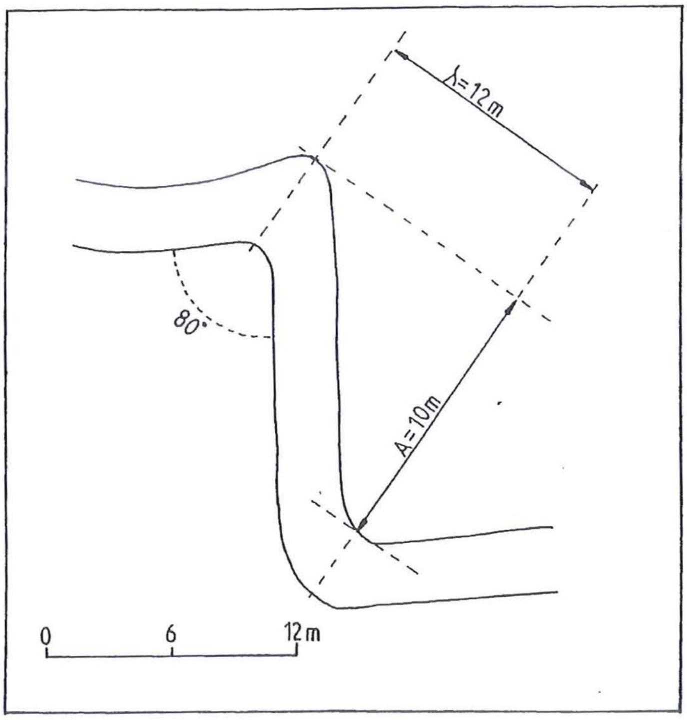


Fig.20. Sketch of typical RLF_1 folding style.

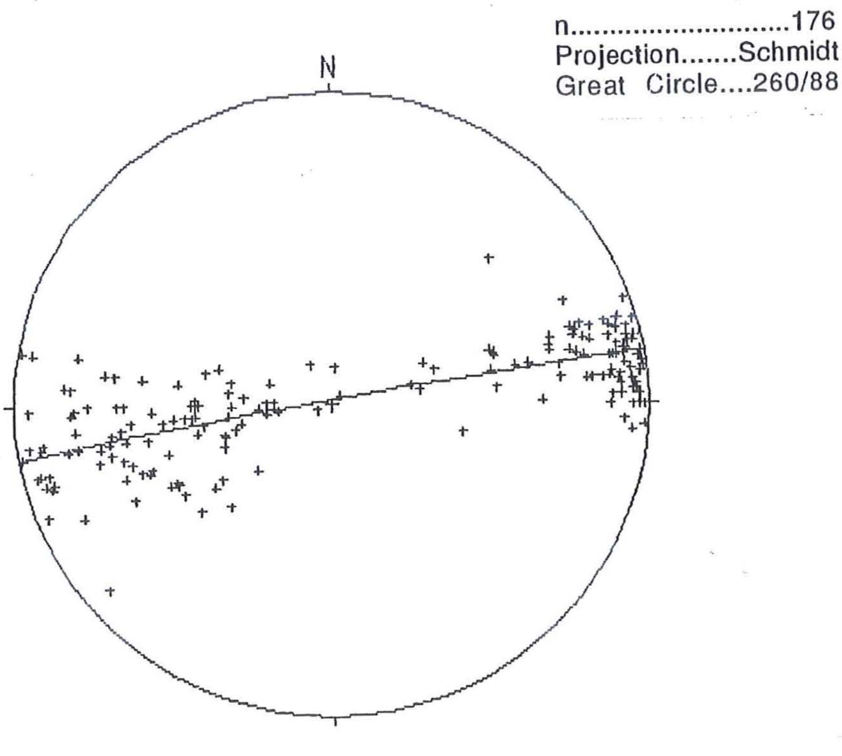


Fig.21. Roaring Lion Formation. Poles to bedding.

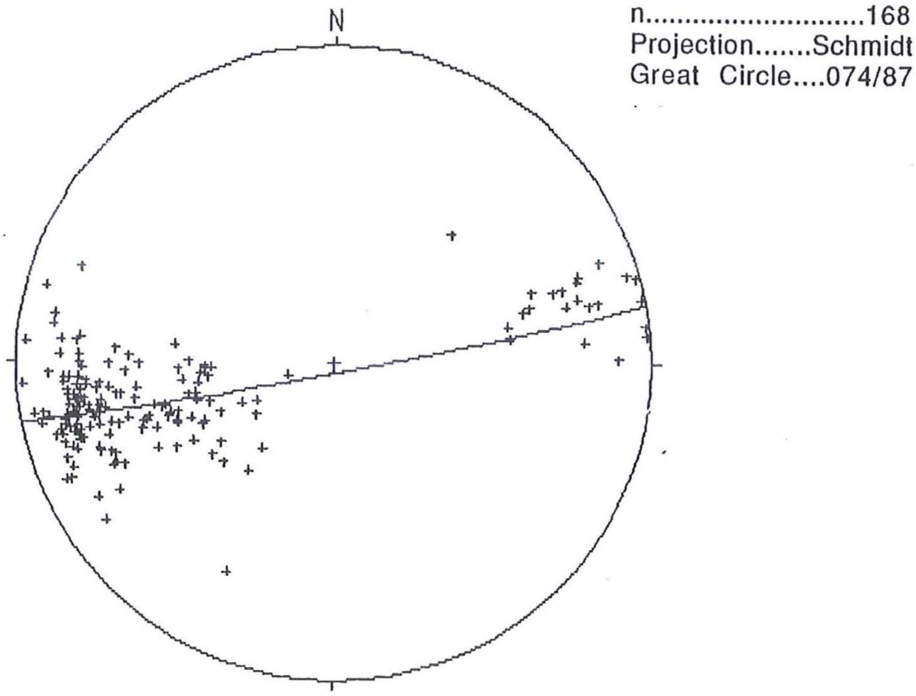


Fig.22. Roaring Lion Formation. Poles to cleavage (RLS_1).

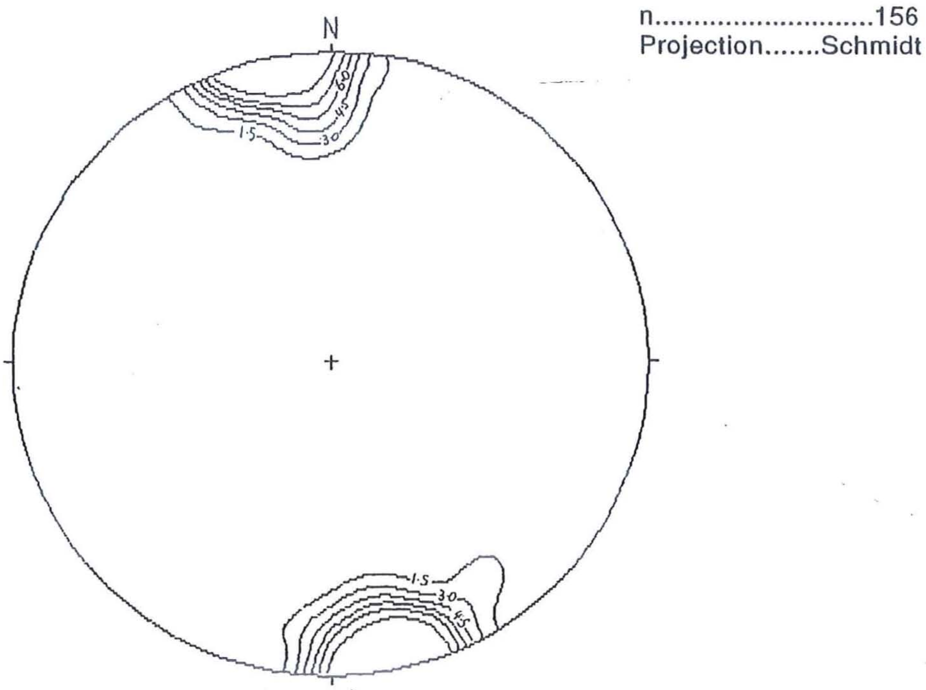


Fig.23. Roaring Lion bedding cleavage intersection lineations (RLL_1). Contour interval=1.5%.

as preceding the deposition of the Lower Devonian Reefton Group.

Adams *et al.* (1975) who obtained a K/Ar date of 395 to 438 Ma of cleavage within the Greenland Group, thought folding and associated metamorphism was Late Ordovician or Early Silurian, a date adopted by Cooper (1979a, 1989) and Cooper and Tullock (1992). Bradshaw (1992) notes that the base of the Silurian has since changed somewhat, and is now thought to be 438Ma. This places the K/Ar dates of Adams *et al.* (1975) entirely within the Silurian.

Grindley (1978) has probably wrongly ascribed the folding of the Roaring Lion Formation (RLF_1 here) to the Tuhua 'F2' deformation. It is much more likely that RLF_1 folding was caused by the same event which deformed the Greenland Group. The style and orientation of folding; and degree of metamorphism of the Greenland Group and Roaring Lion Formation is very similar. Grindley (1980) placed the "Greenland Deformation" (which is distinct from the Tuhua 'F2' deformation) as pre-Tuhua in the latest Ordovician to early Silurian. The "Greenland Deformation" is the same as the Greenland Tectonic Event of Cooper (1979a, 1989) and Cooper and Tullock (1992).

Here RLF_1 is correlated with the Greenland Tectonic Event.

<u>RLF_2</u>: Upright moderately plunging folds outcrop on a ridge west of Waingaro Peak in the Roaring Lion Formation (Fig.24). They trend from ESE to SE and plunge from 40 to 60^0 to the southeast. RLF_2 folds RLF_1 cleavage. RLF_2 fold morphology is classified as similar, close, symmetric folds with wavelengths in the order of 50 metres (Fig.19). No cleavage is associated with the folding.

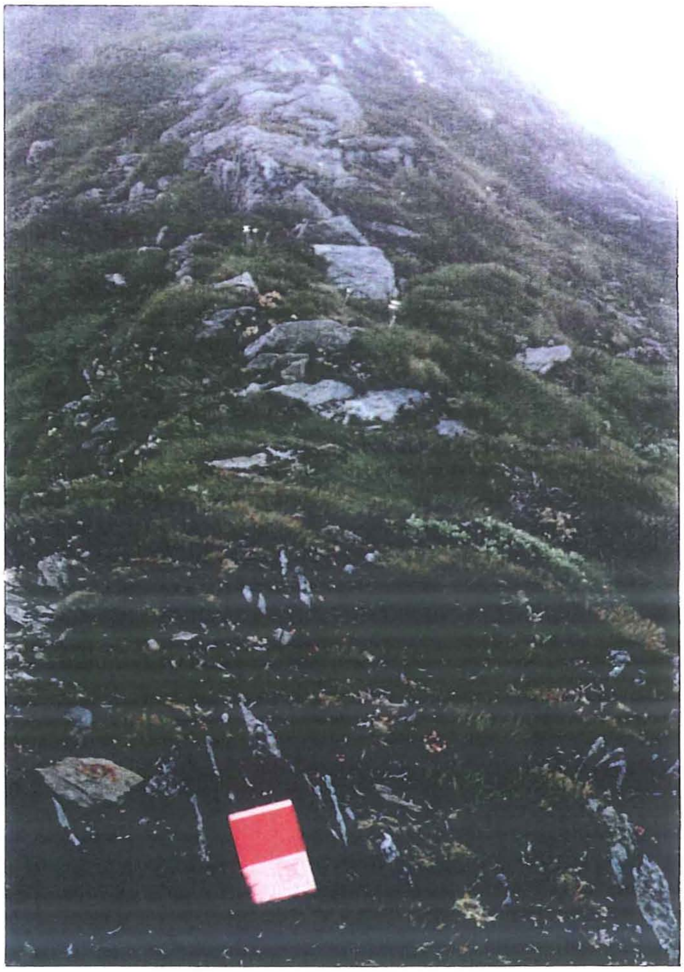


Fig.24. RLF_2 folding west of Waingaro Peak. View looking south. Notebook lies on south striking beds, in the background beds strike approximately west with a concealed fold axis plunging steeply to the southwest in between.

RLF_2 folds are in the vertical eastern limb of a RLF_1 syncline and are not near RLF_1 fold axes, so complex superimposed folding is not present. The folds are localised and not developed anywhere else within the field area, although outcrop is poor along the Roaring Lion Formations eastern margin.

TIMING

Folding was probably contemporaneous with movement of the adjacent FFZ. Fold orientations are consistent with northwest-southeast compression.

<u>DOMAIN TWO</u>: Aorangi Mine, Leslie, Douglas and Peel Formations of the Golden Bay Group.

<u>GBF_1</u>: GBF_1 is represented by a slaty cleavage (GBS_1) developed throughout Domain 2 at a low angle to bedding (Fig.25). No folds are associated with GBS_1. In the sandy lithologies of the Douglas and Peel Formations GBS_1 is less well developed than in the Leslie and Aorangi Mine Formation where it is very marked.

GBS_1 most probably formed as a response to compaction and metamorphism of the sedimentary pile.

<u>GBF_2</u>: The Fenella Fault Zone.

Cooper (1989) recognised a zone of faulting and folding running from Boulder Lake 60 kilometres south to the Wangapeka area, and named it the Fenella Fault Zone. He describes it as containing: "*tight, plunging folds and anastomosing faults*" (1989, p109). In the field area the FFZ involves the entire Aorangi Mine Formation and part of the Leslie Formation.

Rocks in Domains 1 and 2 were brought together by the FFZ. They are not a conformable sequence as mapped by Grindley (1980). At the Roaring Lion Formations eastern margin, RLF_1 fold axes are absent and all beds dip consistently near vertical and young to the west, <u>away</u> from the younger Golden Bay Group. Further points of evidence

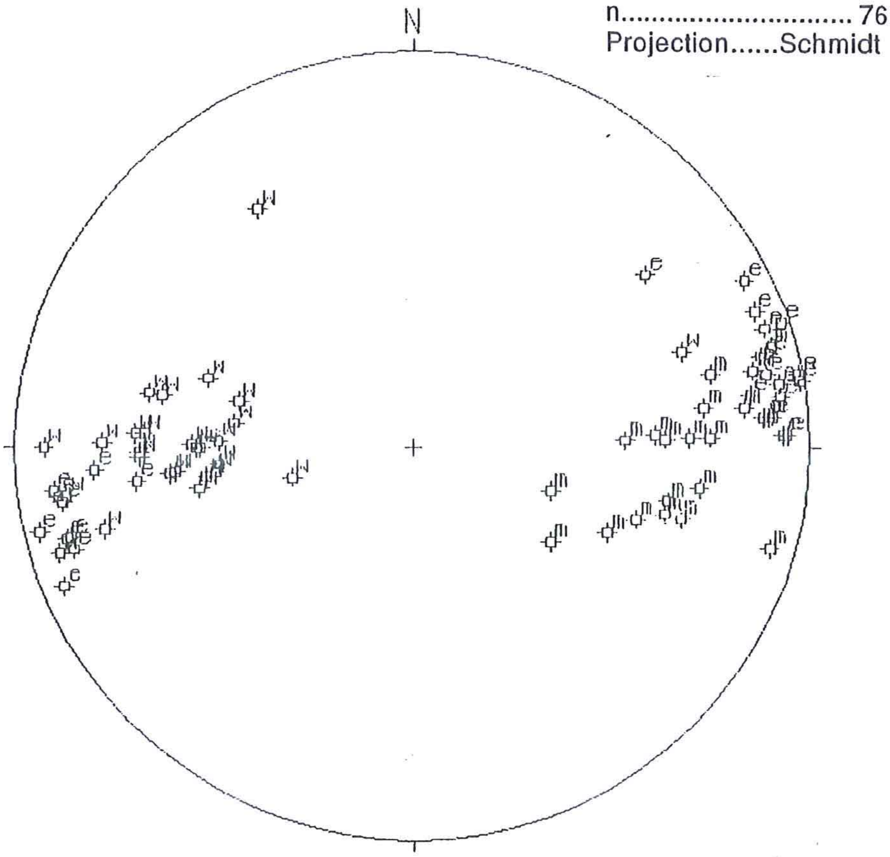


Fig.25. Domain 2, poles to GBS_1 (parallel to bedding). W, M and E=western, middle and eastern fault bounded blocks as shown in Fig.26.

which suggests the FFZ is a major discontinuity are:

1) For the Roaring Lion Formation and Golden Bay Group to be concordant an extra anticline is needed between the west facing beds of the Roaring Lion and the east facing Golden Bay Group. One was not seen.

2) If this hypothetical anticline exists one may expect rocks of the Golden Bay Group to outcrop in part on top of the Roaring Lion Formation to the west. This is not seen to happen.

3) The structure becomes very unlikely if the Golden Bay Group is folded about the hypothetical anticline.

4) The structural styles of Domain 1 and Domain 2 are quite different.

FAULTS

The structures of the FFZ are dominated by steeply dipping faults relatively concordant to bedding which strike north (Fig.26).

Both major quartzite bands of the Aorangi Mine Formation are faulted on at least on side (Fig.27). Yet the same bands have been traced along the FFZs length for many kilometres. This lateral persistence of bedding is only possible if the faults remain concordant to bedding.

Faulting has removed a considerable thickness of the Aorangi Mine Formation. Proof of this is supplied by the Bendigonian age of the Aorangi Mine Formation within the FFZ published by Cooper (1989). The adjacent Leslie Formation is not older than Upper Darriwilian. The intervening rocks representing a time span covering the Chewtonian, Castlemainian and Yapeenian stages are only a few metres thick and therefore have been

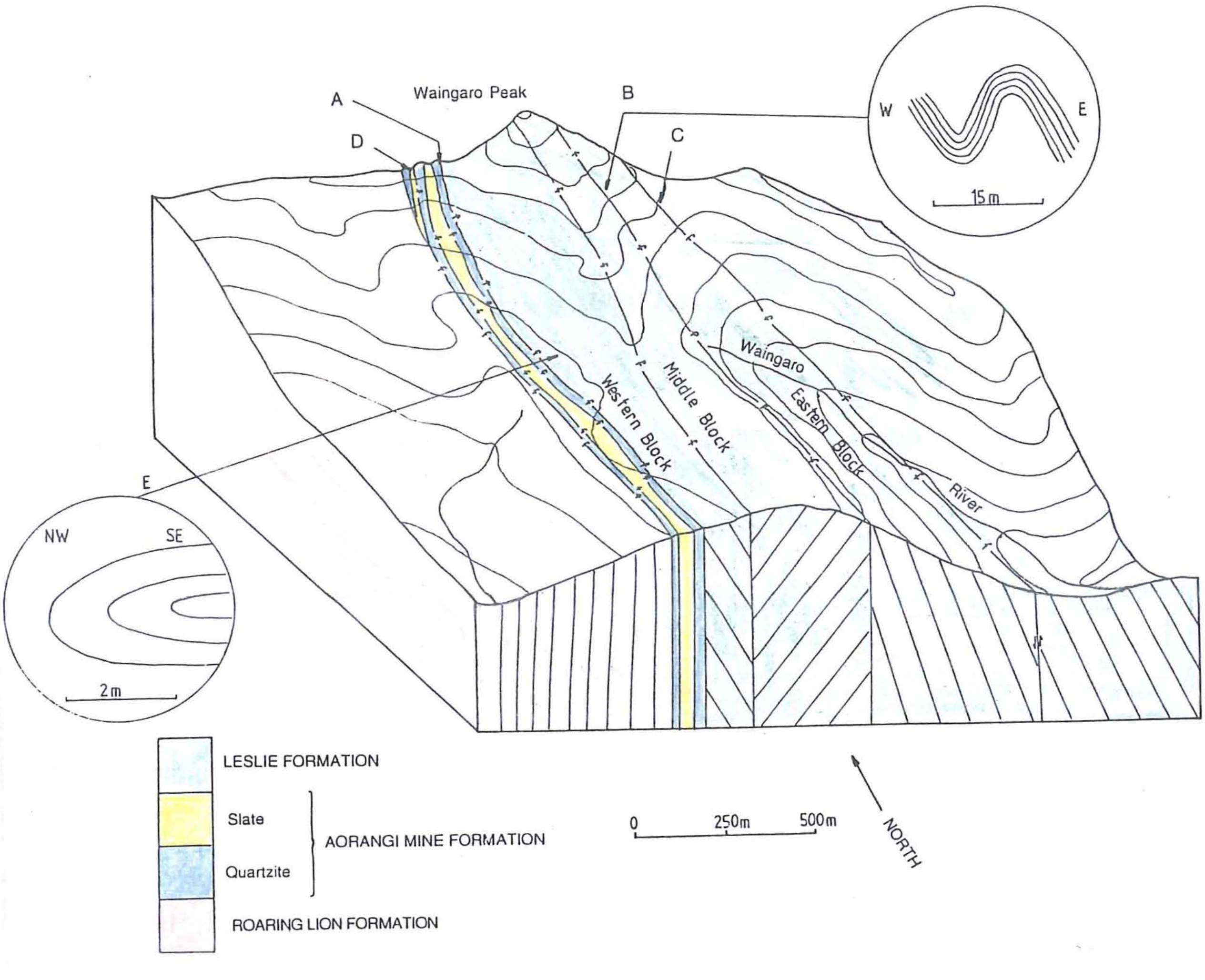


Fig.26. Schematic block diagram of the area south of Waingaro Peak illustrating folds associated with GBF_2. Letters mark locations referred to in the text.

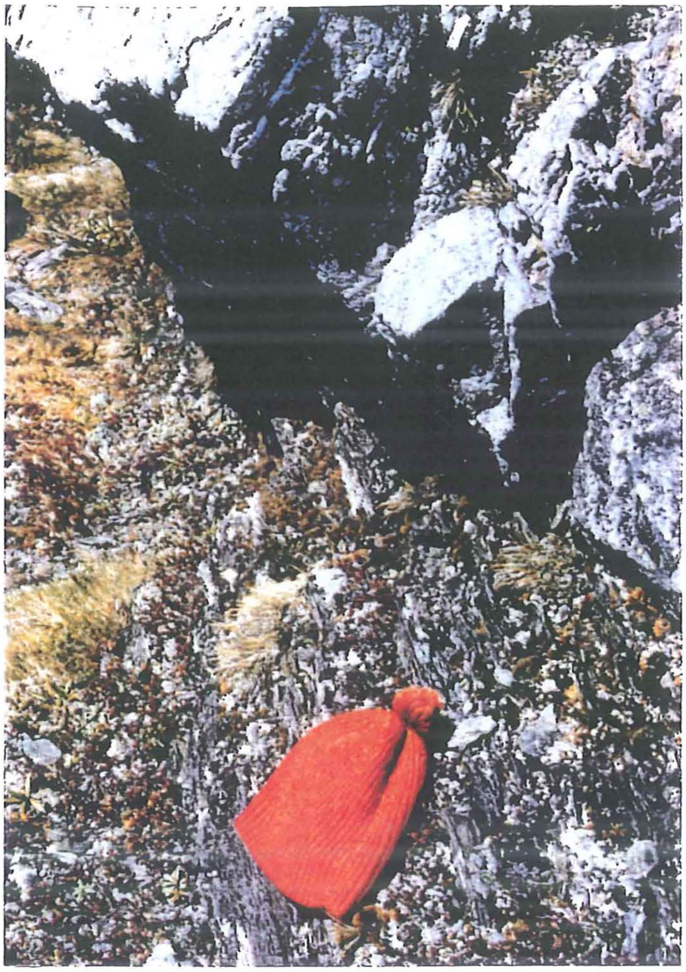


Fig.27. Fault contact between Aorangi Mine Formation quartzite and Leslie Formation slate. View looking south. (Location A, Fig.26).

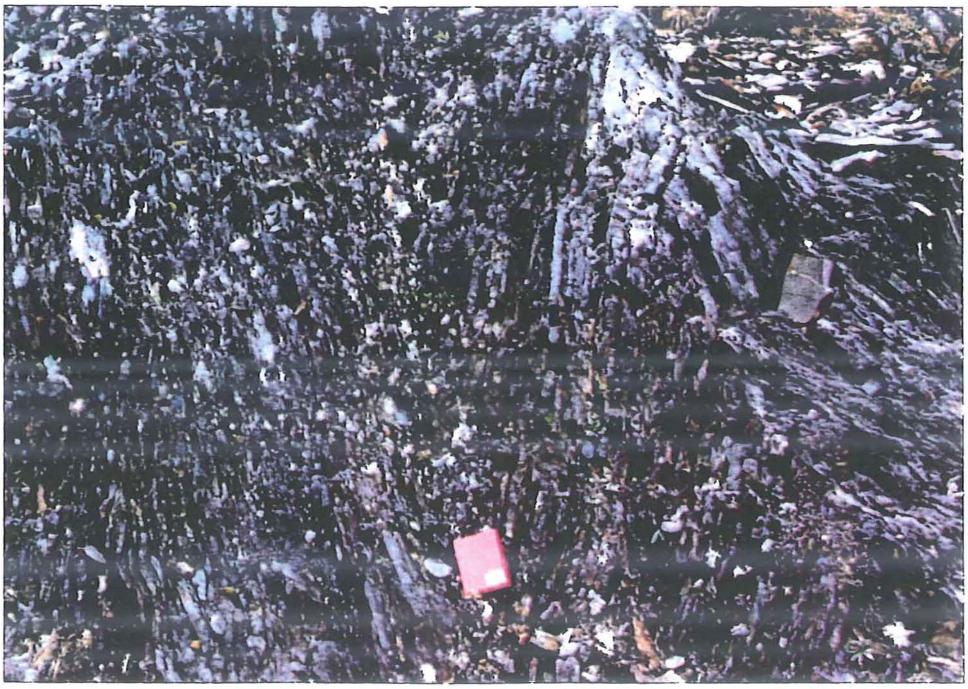


Fig.28. Drag fold adjacent to GBF_2 fault in the Leslie Formation. The notebook lies on the fault with an antiform to the right. View looking north. For scale notebook is 17cm long.

severely thinned or cut out.

Although the Leslie Formation is also faulted by GBF_2 Skwarko (1962) recorded an undisrupted sequence of graptolite fauna. Therefore faulting in the Leslie Formation could not have either removed a great thickness of strata, or emplaced younger strata between older strata and vice versa. However Section A-A'(Appendix 3) and Figure 26 show a fault bounded block within the Leslie Formation which comprises west dipping beds. Slates to either side of this block dip eastward. This indicates that although the Leslie Formation has not been thinned greatly, significant movements occurred.

Only the eastern most fault in Figure 26 (location C) gives a sense of movement. Here a drag fold indicates reverse movement took place on the east dipping fault (Fig.28). Slickensides are absent from all fault planes.

FOLDS

Five folds were observed in the FFZ. The first involves slates of the Leslie Formation (Location C Fig.26). GBS_1 cleavage is folded by a drag fold adjacent to a reverse fault. It is a tight fold with an upright sub-horizontal attitude with the fold axis oriented 170/10N (Fig.28).

The second and third folds are a small syncline anticline pair within the Leslie Formation (location B Fig.26). GBS_1 is folded. The fold axes are oriented 175/5N, and the wavelength is 20 m.

The fourth fold involves slate and quartzite of the Aorangi Mine Formation (location D

Fig.26). It is a synform oriented 164/16 NW. Fold morphology is upright and open. Curvature of the folds inner arc is less than the outer arc, and therefore it is of the Class 3 folding of Ramsay (1967) (Fig.29).

The fifth fold (location E Fig.26) is reclined closing to the north with a fold axis orientation of 044/47N.

The FFZs sense of movement and timing is discussed at the end of the chapter.

GBF_3: GBF_3 is represented by the second of the three cleavages (GBS_2) in the Douglas and Peel Formations and is very weakly developed in the Leslie Formation. It dips steeply to the east and cross cuts bedding at an angle of 30^0. GBS_2 is the least well developed of the cleavages and is only properly seen in thin section (Fig.30). It dextrally offsets bedding and GBS_1 as viewed from above.

No folding is associated with GBS_2 and it is thought to have formed during the initial stages of GBF_4 deformation (Fig.31).

GBF_4: GBF_4 is recognised by the presence of a third cleavage (GBS_3) which postdates GBS_2. Without exception it dextrally offsets bedding and the two earlier cleavages when viewed from above (Fig.30 and 32). GBS_3 dips steeply northwest or southeast and strikes 025^0 on average (Fig.33). In outcrop it is not well developed throughout the entire domain. GBS_3 surfaces are seen in the Leslie and lower Douglas Formation until outcrop becomes poor toward the east.

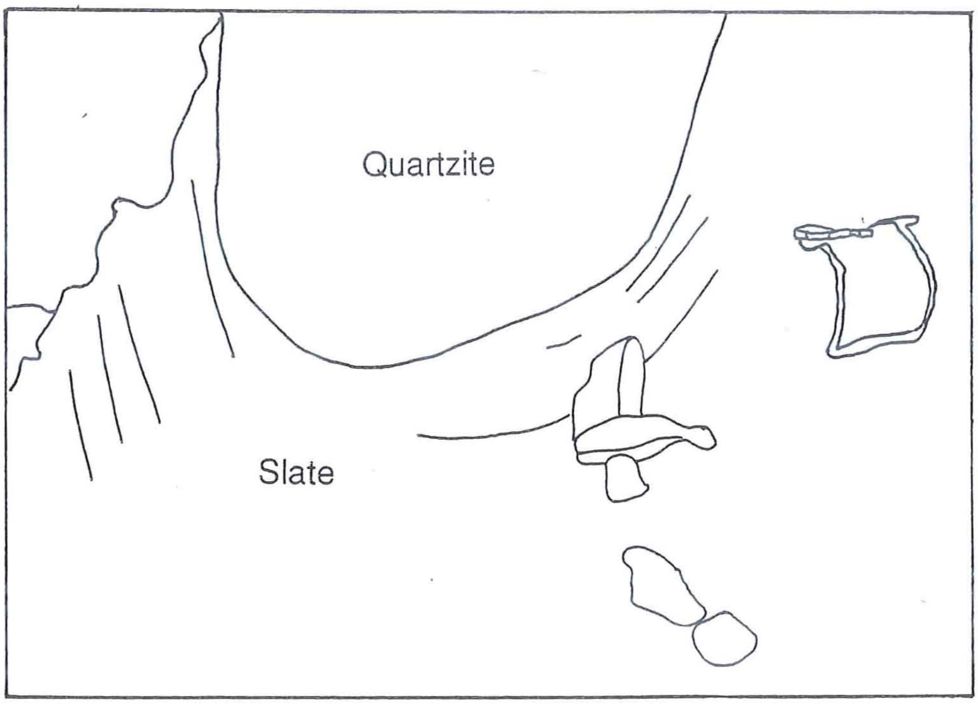
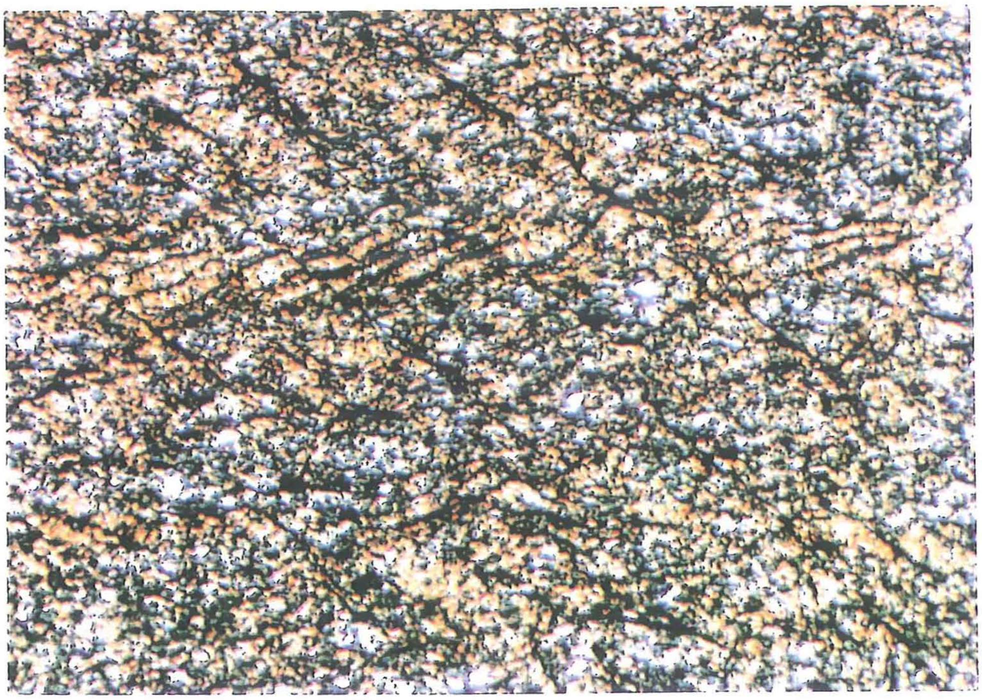


Fig.29. Fold involving slate and quartzite of the Aorangi Mine Formation. View looking north. Compass for scale.



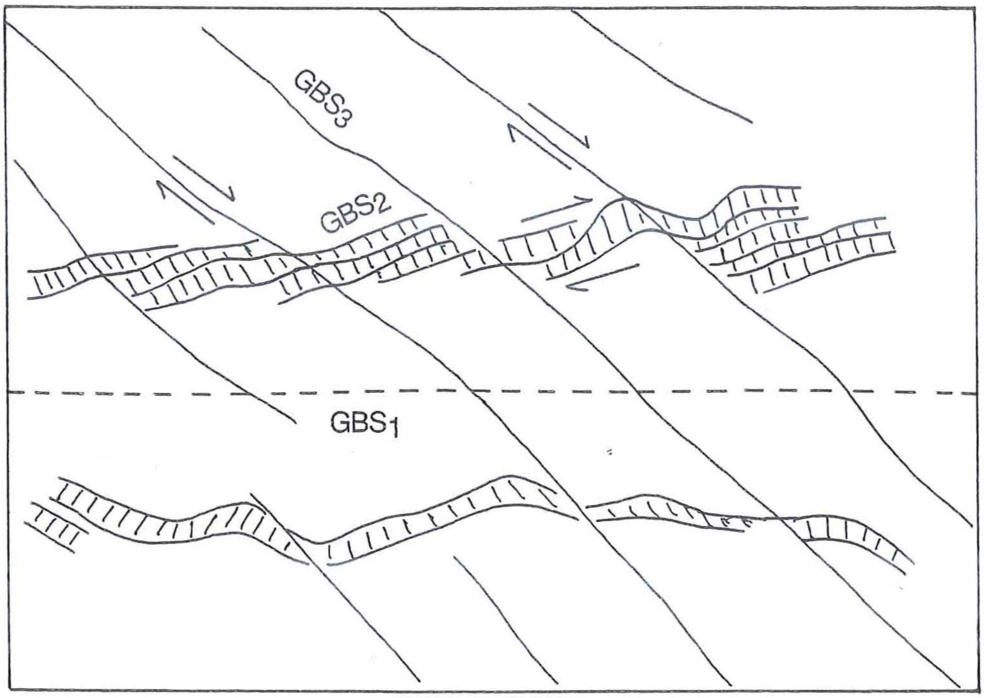


Fig.30. Photomicrograph of the Douglas Formation (Sample KP3). Mag.x10 Crossed polars. Line drawing shows the relative positions and offsets on GBS_1, GBS_2, and GBS_3.

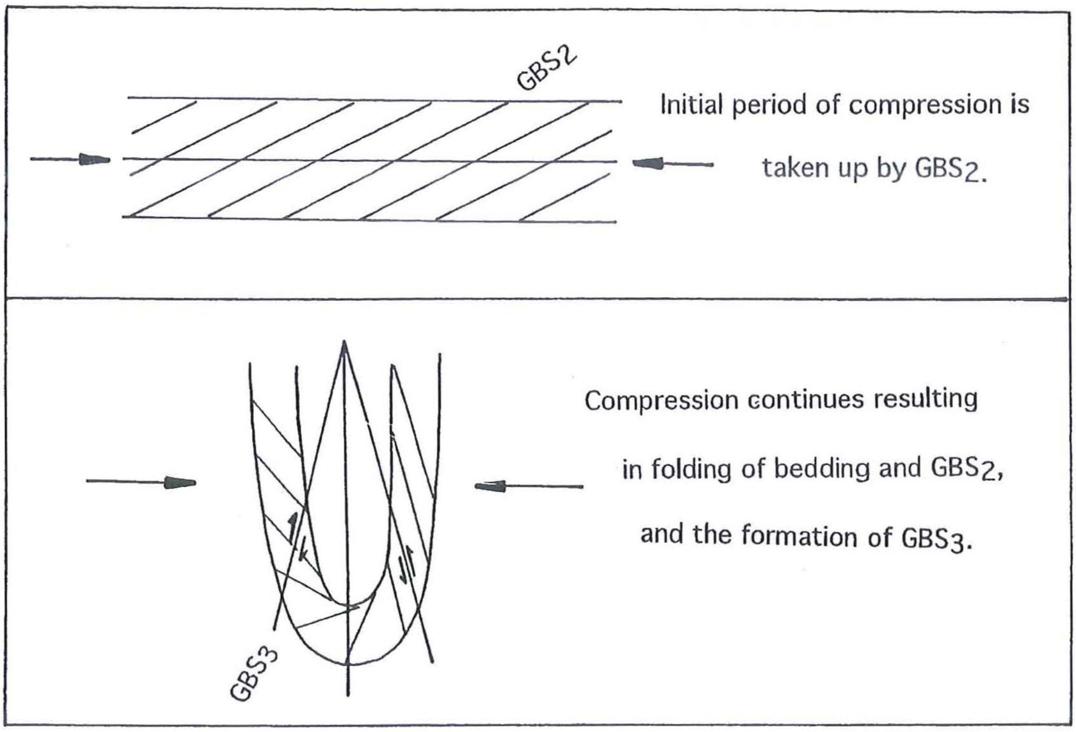


Fig.31. Schematic sketch illustrating the origin of GBS_2 and GBS_3.

Fig.32. GBS$_3$ in the Douglas Formation dextrally offsetting north striking bedding. For scale pencil=15cm.

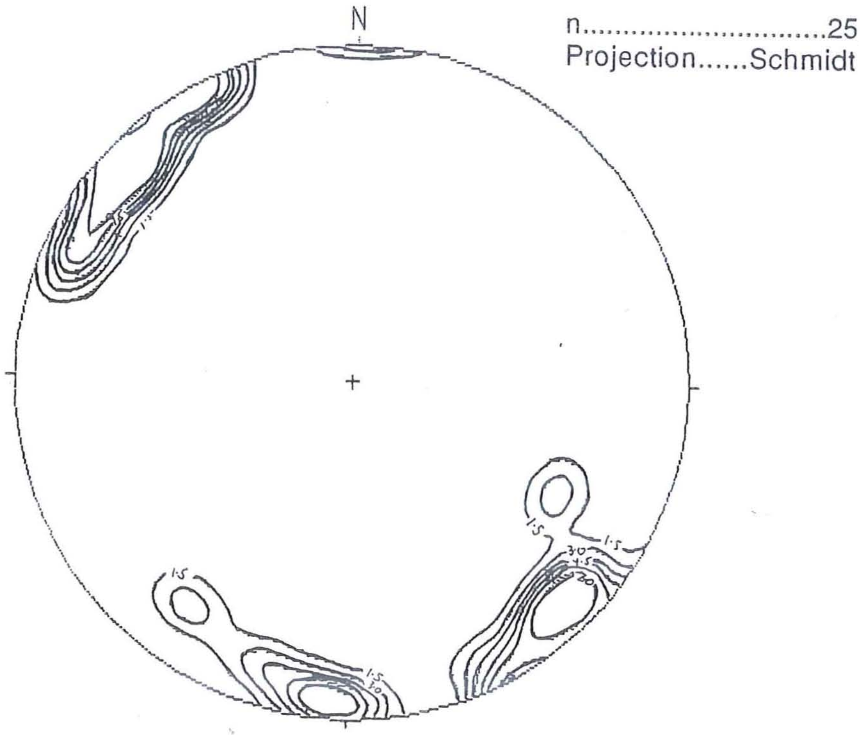


Fig.33. Domain 2, poles to GBS$_3$. Contour interval=1.5%.

Unfortunately GBS_2 and GBS_3 were not seen in the rocks folded by the FFZ, and so the relative time of GBF_2 deformation cannot be confirmed here. However a possible set of GBS_2 surfaces was seen at one locality at the western margin of the Roaring Lion Formation. The orientation and offset here is consistent with GBS_3 surfaces in Domain 2 (Fig.34) and suggests Domains 1 and 2 must have been adjacent to the time of GBF_4 deformation.

Although GBS_3 suggests associated folding to have an axial plane(s) striking 025^0, folds of this orientation do not occur in the rocks within Domain 2, which consistently strike northward. Rather it is inferred that the axial plane is parallel to bedding, and the cleavage fans out about the fold axis which must be sub vertical. The dextral offsets indicate that the GBS_2 surfaces are in either the eastern limb of a steeply plunging antiform or the western limb of a steeply plunging synform (Fig.35). Because GBS_3 is developed past the western margin of Domain 2 and no folding is seen here or further to the west, GBS_3 indicates a steeply plunging synform to the east (Fig.19). Outcrop is limited to the east of Domain 2 and the folding was not seen.

GBF_4 is thought to be a continuation of GBF_3 deformation. GBS_2 has recorded an initial stage compression which preceded GBF_4 folding. Unfortunately neither cleavage is developed in the east of Domain 2 where they should be approximately parallel.

Cooper and Tullock (1992) map a syncline in the Douglas Formation with an overturned eastern limb and minimal plunge which continues for approximately 15 km trending north. They do not provide any evidence supporting the steeply inclined-sub horizontal fold they map.

Fig.34. North striking Roaring Lion Formation near the eastern margin of Domain 1 dextrally offset by possible GBS_3 surfaces. View measures 30cm across.

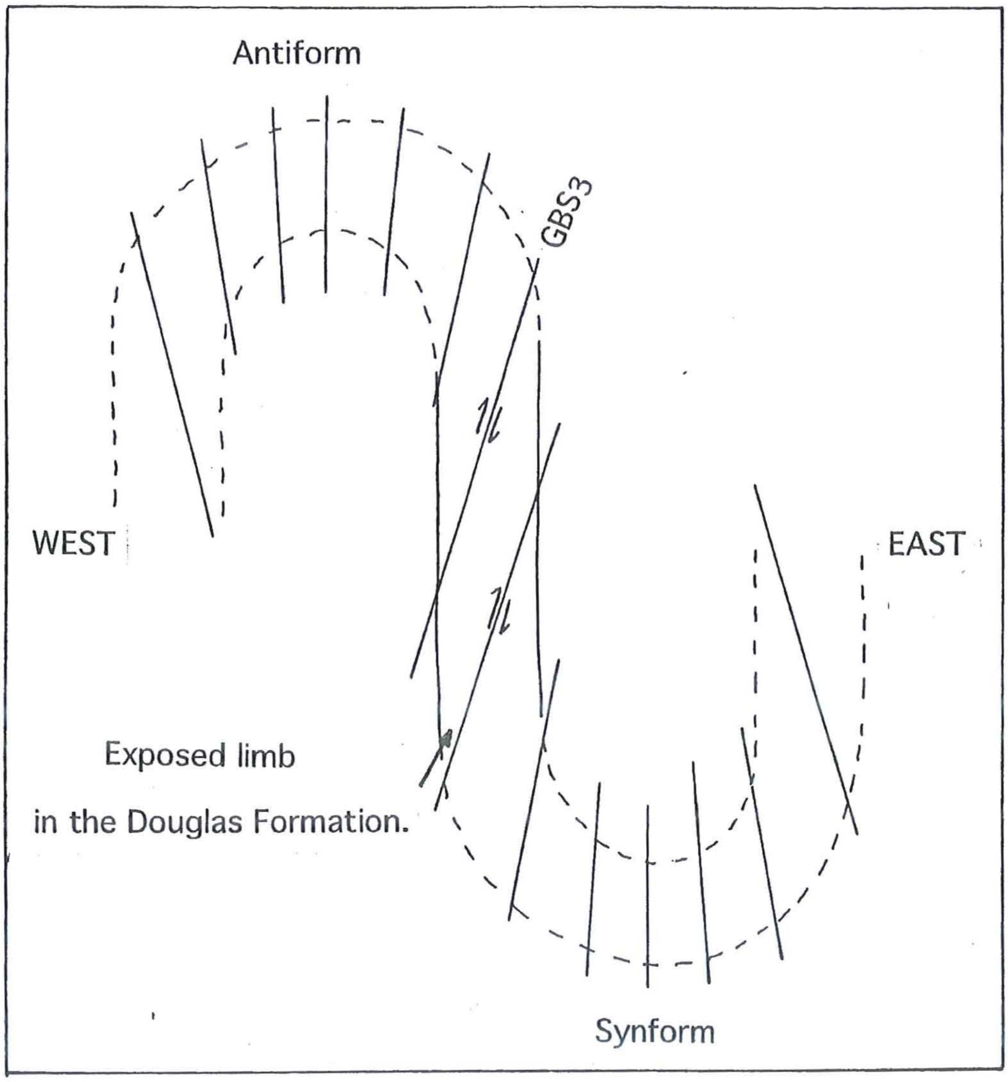


Fig.35. Schematic sketch of possible GBF_4 folding. Bedding-cleavage relationships indicate a synform to the east or an antiform to the west of Domain 2.

Bishop (1968b) described complex folding in the Ordovician shales and quartzites of the Gouland Downs to the north of the field area (Fig.1). Folding styles here are predominantly isoclinal with steeply plunging axes trending approximately north to northwest. Bishop also notes that "*A striking feature of the folds is the lack of fold noses closing to the north.*" (1968, p606). These characteristics are consistent with the fold orientation indicated by GBS_3. Folding at the Gouland Downs and of Domain 2 could represent the same event. Indeed Bishop equates the folding at Gouland Downs with folding described by Grindley (1961) which was caused by emplacement of the Central Belt nappes. Later Grindley (1971, 1978 and 1980) described: "*reclined recumbent folds in Western Belt rocks with similar attitudes and vergences to those in the Central Belt, especially in the Douglas Formation below the Anatoki Thrust.*" (1980, p27).

Due to the proximity of the Anatoki Thrust it is possible that GBF_3 and GBF_4 are related to movements on the Anatoki Thrust, though not necessarily with emplacement of nappes from the south.

JOINTS AND RECENT FAULTS

The whole field area is well jointed. Most joints strike east-west (Fig.36). There is only limited evidence of recent faulting. Fig.37 shows a possible fault running along the ridge above Fenella Hut marked by a change in the vegetation. Recent faulting does not effect the geology significantly.

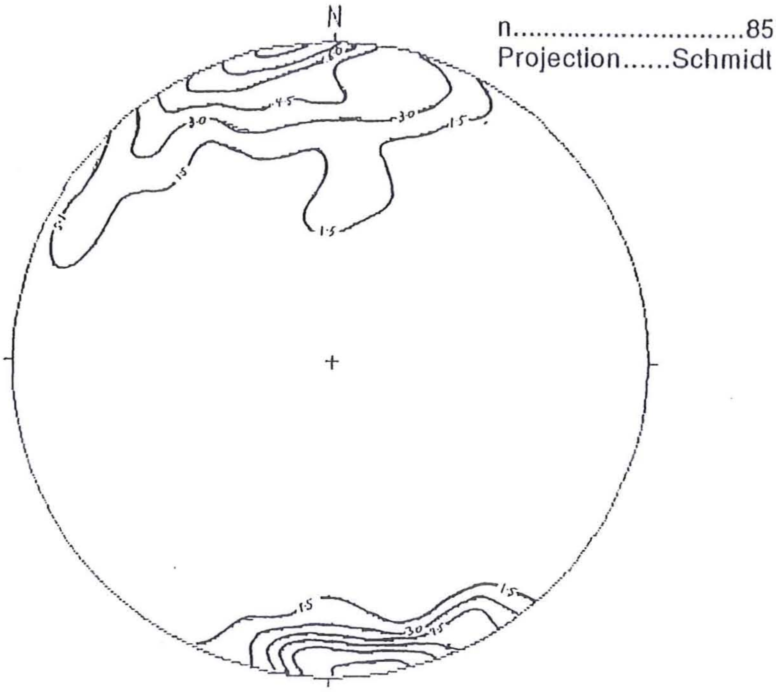


Fig.36. Domains 1 and 2, poles to joints. Contour interval=1.5%.

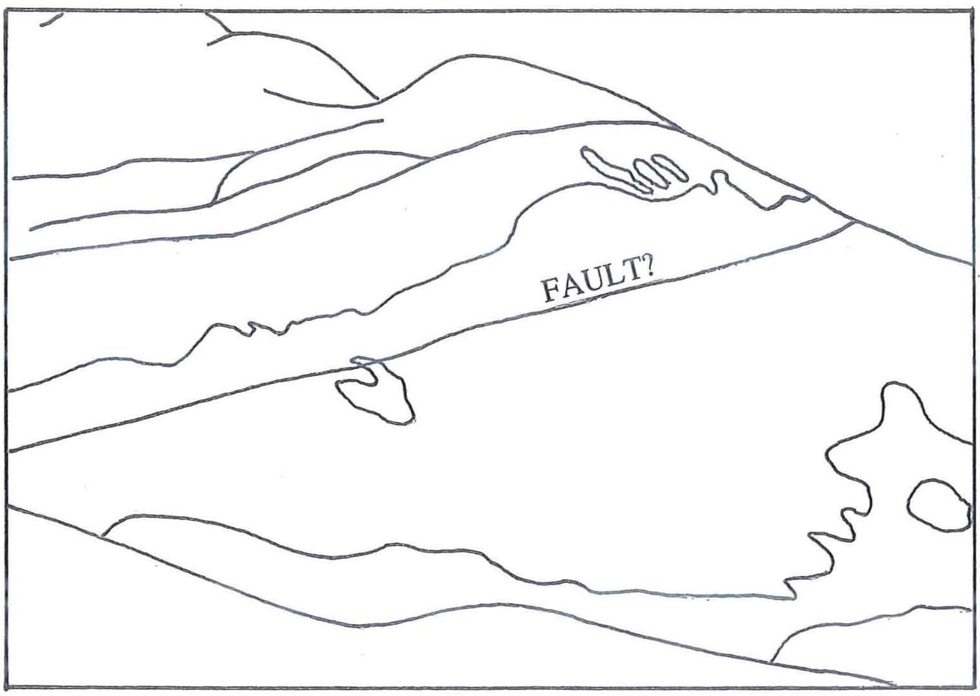


Fig.37. Possible recent fault marked by a break in vegetation. View looking south to the Cobb Valley.

DISCUSSION

Determination of the FFZs sense of movement is problematic. Only the eastern most fault gives a sense of movement (reverse). Any structural modelling of the FFZ must take into account the following facts:

1) The FFZ is a steeply dipping fault zone.

2) Faults within the FFZ are approximately concordant to bedding.

3) The FFZ has removed a considerable thickness from the Aorangi Mine Formation and possibly the base of the Leslie Formation.

4) The FFZ is relatively narrow and continuous for a great distance.

5) Movement of the FFZ is constrained by the Late Ordovician to Early Silurian RLF_1 which it cuts and the Cretaceous Mount Olympus Pluton which cuts it (Cooper, 1989).

6) The Aorangi Mine Formation is not seen west of the FFZ, and the Roaring Lion is not seen east of the FFZ.

The FFZ is the fault zone along which Domains 1 and 2 were brought together. The faulting together may have simply involved the removal of a section (Aorangi Mine and Roaring Lion Formations?) within an originally conformable sequence. However it is more likely that the structural history is more complex than this.

The distinct structural styles of Domain 1 and Domain 2 require the two domains to have been quite separate at the time of GBF_1 deformation. Even if the sequence included the full thickness of Aorangi Mine Formation separating the two domains, Domain 2 would not have been immune to RLF_1 folding which is seen in rocks from Westland to Northwest Nelson.

A possible explanation for the absence of RLF_1 folding within Domain 2 to note, is that Domain 1 may not have been separated from Domain 2 by distance, but by time. This theory is easily disproved. The Late Ordovician to Early Silurian deformation postdates the Early to Middle Ordovician Aorangi Mine Formation and Golden Bay Group. The rocks did exist at the time of RLF_1 folding.

The different structural styles of the two domains may in part be due to their relative positions in the sedimentary pile. The Roaring Lion Formation has been subjected to low greenschist facies metamorphism with pressure solutioning of quartz grains. The adjacent quartzites of the Aorangi Mine Formation have retained their original sedimentary character with little deformation of quartz. The Roaring Lion Formation must have been at a deeper structural level than the rocks of Domain 2. While RLF_1 folded the Roaring Lion Formation, the Aorangi Mine - Leslie - Douglas - Peel sequence was only subjected to relatively low pressure temperature conditions at a higher structural level, which formed GBS_1.

Movement on the FFZ during GBF_2 deformation brought the two Domains together. If Domain 1 originally was deeper than the rocks of Domain 2, it must have been faulted upwards by the FFZ to be adjacent to Domain 2. The dip (if any) of the FFZ at this time is unknown. Regionally the Paleozoic rocks of Northwest Nelson are dominated by compressional structures formed from east - west shortening. Cooper and Tullock (1992) have drawn at least seven thrusts in a section from the Roaring Lion Formation to the Devil River Fault. Geometrically the steeply dipping FFZ is at odds with the dominantly east dipping thrusts of the Western and Central Sedimentary Belts. An explanation for the FFZs orientation is that it was originally a relatively low angle structure which became inactive and steepened up under the continuing compressional regime. GBF_3 folding may have assisted in this steepening process. If the FFZ originally dipped to the east like the other faults it would of been a normal fault. If it dipped westwards a reverse sense of movement is required to bring the Roaring Lion Formation up.

It is a distinct possibility that the FFZ involved a considerable strike slip component, as well as the vertical component required to bring the two domains together. With a strike slip model one would expect to see a thickening of the FFZ along strike where faulted slivers were emplaced. It is easier to account for removed strata by thrusting or normal faulting.

The view favoured here is that the FFZ was originally a west dipping thrust locally concordant to bedding. Structures RLF_1, RLF_2, folds within the FFZ, GBF_4, and to some extent GBF_3 represent deformation with a significant component of east-west compression. In Northwest Nelson Paleozoic tectonic structures were driven by the suturing of the Takaka and Buller terranes along the Anatoki Thrust. Therefore it is likely, if not highly probable, that the FFZ was also driven by east-west compression.

SUMMARY

The order of structural events are as follows.

1) RLF_1 folding in Domain 1 associated with lower greenschist facies metamorphism. At this time Domain 2 was distant and at a higher structural level, where GBS_1 was developed.

2) Under a compressional regime Domain 1 is thrust up adjacent to Domain 2, with a considerable strike-slip component possible. The Aorangi Mine Formation is thinned and RLF_2 folding occurs.

3) GBS_2 and GBS_3 form under continuing compression with associated folding. GBF_3 and GBF_4 may have in part been contemporaneous with GBF_2 (FFZ) movement.

4) The Fenella Fault Zone becomes inactive and is steepened up.

CHAPTER FIVE

GEOCHEMISTRY

INTRODUCTION

The Greenland Group is an Ordovician turbidite succession which outcrops discontinuously from Milford Sound to Karamea on the West Coast of the South Island. It consists of alternating indurated grey-green quartz rich sandstone and mudstone beds. The aim of this chapter is to define the degree of similarity the Greenland Group has with the Roaring Lion Formation, by the comparison of geochemical analyses.

BACKGROUND

The similarity between the Greenland and Aorere Groups has long been recognised. Bell described *"Arkosic grauwackes, argillites, minor bands of conglomerate, and schistose rocks"* (1906, p46), which he included in the Kaneri Series of the Hokatika Sheet. Morgan (1908) renamed these rocks as the Greenland Series because Kaneri had previously been used to describe Tertiary sediments. However Park (1910) used the name Kaneri when describing Aorere rocks near Collingwood, and in doing so established a link between the Paleozoic basement of Northwest Nelson and Westland.

Henderson (1917) regarded the Greenland and Aorere Series as equivalents "...*rocks of the Aorere (or Greenland) Series...*" (1917, p69).

The absence of fossils dating the Greenland Series was a major stumbling block for the correlation with the Ordovician Aorere Series. The identification of lower Ordovician graptolites recovered from the Waiuta Group by Cooper (1974) was an important discovery. Thus once again comparisons could be drawn between the Greenland and Aorere Groups. Cooper(1979a) included both groups in his Western Sedimentary Belt, also defined as the Karamea (now Buller) terrane by Bishop *et al.* (1985).

Grindley (1980) believed "*The Greenland Group of Westland...must be a part correlative of the Aorere Group of Northwest Nelson.*" (1980, p14). Finally Cooper(1989) suggested expanding the Greenland Group to include the Roaring Lion and Webb Formations.

Despite the numerous papers which mention the similarities between the Greenland Group and Roaring Lion Formation, no worker has justified their conclusions other than by field descriptions. The geochemistry which follows attempts to fill this gap in our knowledge.

GEOCHEMISTRY

Seven samples of Roaring Lion Formation and two samples of Greenland Group have been analysed for major and trace element geochemistry by means of X-ray fluorescence. These data has been supplemented by analyses of two Greenland Group enclaves contained within the Cape Foulwind Granite, reported by Smith (1992); and eleven Greenland Group analyses of Nathan (1976). Nathan's FeO_2 has been recalculated so that it now represents total iron to match the remaining data (Table 2). In all of the following plots the major elements have been recalculated to 100% LOI free.

The two Greenland Group analyses published here conform with those analysed by Nathan (1976). As expected enclaves within the Cape Foulwind Granite (Smith, 1992) show some geochemical irregularities. These analyses plot at the extreme of the Greenland Groups range and so are treated with caution here. Nevertheless all data points maintain easily recognisable trends when plotted on variation diagrams (eg Fig.38).

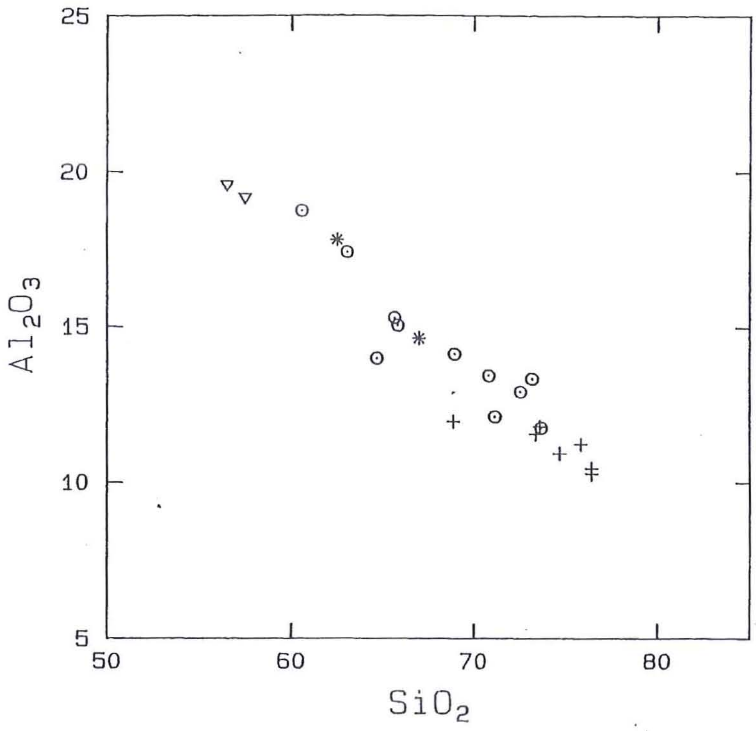
The range of SiO_2 from 69 to 76% for the Roaring Lion Formation is clearly higher than the Greenland Groups range of 56 to 74%. Nathan (1976) found that Greenland Group geochemistry was characterised by $K_2O > Na_2O$, $CaO < 1.5\%$ and $Rb >> Sr$. These characteristics are useful for comparison with the Roaring Lion Formation.

	1	1	1	1	1	1	1	2
Sample	24686	24687	24688	24689	24690	24691	24692	24693
SiO_2	73.43	76.37	69.16	75.99	74.69	73.80	74.74	66.19
TiO_2	0.68	0.64	0.64	0.59	0.71	0.62	0.55	0.70
Al_2O_3	11.57	10.45	12.03	10.22	10.94	11.86	11.08	14.48
Fe_2O_3	4.39	3.81	4.66	3.70	4.22	4.24	3.89	5.66
MnO	0.04	0.05	0.05	0.05	0.06	0.06	0.11	0.05
MgO	2.17	1.46	2.18	1.51	1.90	1.81	1.59	2.92
CaO	0.53	0.55	0.99	0.90	0.84	0.77	0.81	1.30
Na_2O	1.78	1.59	1.49	1.65	1.76	2.02	2.02	1.83
K_2O	2.36	2.16	2.61	2.09	2.10	2.26	2.07	3.18
P_2O_5	0.19	0.19	0.18	0.17	0.24	0.20	0.17	0.18
LOI	2.91	2.67	6.45	2.56	2.51	2.64	1.53	2.34
Total	100.05	99.94	100.44	99.43	99.97	100.28	98.56	98.83
V	73.00	67.00	76.00	63.00	69.00	74.00	67.00	100.00
Cr	63.00	59.00	63.00	52.00	67.00	59.00	52.00	76.00
Ni	30.00	24.00	31.00	25.00	29.00	30.00	26.00	34.00
Zn	73.00	59.00	77.00	60.00	68.00	69.00	67.00	94.00
Zr	233.00	348.00	212.00	238.00	426.00	222.00	162.00	160.00
Nb	10.00	11.00	12.00	10.00	10.00	11.00	11.00	11.00
Ba	390.00	348.00	451.00	384.00	320.00	371.00	350.00	559.00
La	37.00	38.00	38.00	33.00	49.00	35.00	37.00	43.00
Ce	94.00	90.00	92.00	77.00	106.00	82.00	78.00	86.00
Nd	38.00	39.00	38.00	36.00	41.00	37.00	30.00	36.00
Ga	20.00	20.00	20.00	18.00	18.00	19.00	20.00	21.00
Pb	16.00	11.00	21.00	11.00	10.00	4.00	20.00	11.00
Rb	115.00	103.00	130.00	102.00	102.00	106.00	96.00	148.00
Sr	54.00	55.00	78.00	53.00	60.00	55.00	56.00	83.00
Th	16.00	19.00	16.00	15.00	20.00	16.00	14.00	16.00
Y	34.00	34.00	38.00	28.00	44.00	35.00	31.00	33.00

	2	3	3	4	4	4	4	4
Sample	24694	JS200	JS201	37731	38410	39127	39131	39798
SiO_2	62.26	57.19	56.51	71.00	60.84	72.70	65.25	66.28
TiO_2	0.84	0.77	0.74	0.69	0.76	0.51	0.89	0.67
Al_2O_3	17.76	19.10	19.61	12.10	18.85	12.95	14.13	15.17
Fe_2O_3	6.20	7.80	8.05	5.45	7.15	4.39	7.80	6.21
MnO	0.02	0.04	0.04	-	-	-	-	-
MgO	3.05	4.05	3.95	2.57	3.42	2.22	3.91	2.83
CaO	0.18	0.52	0.27	1.38	0.23	0.71	1.39	0.93
Na_2O	0.91	1.02	0.44	1.49	0.87	0.79	1.68	1.03
K_2O	4.00	4.93	5.73	2.44	5.06	3.57	2.76	4.30
P_2O_5	0.18	0.16	0.15	0.24	0.14	0.09	0.29	0.16
LOI	4.28	3.91	4.54	2.40	3.15	2.25	2.85	3.15
Total	99.68	99.49	100.03	99.76	100.47	100.18	100.95	100.73
V	110.00	140.00	138.00	-	-	-	-	-
Cr	89.00	103.00	106.00	61.00	100.00	68.00	-	82.00
Ni	48.00	50.00	49.00	-	-	-	-	-
Zn	110.00	123.00	123.00	-	-	-	-	-
Zr	163.00	126.00	132.00	-	-	-	-	-
Nb	14.00	13.00	13.00	-	-	-	-	-
Ba	662.00	738.00	760.00	393.00	932.00	492.00	-	589.00
La	47.00	38.00	39.00	36.20	36.80	17.00	-	30.20
Ce	105.00	79.00	92.00	71.20	67.80	35.40	-	54.10
Nd	41.00	-	-	41.00	36.00	-	-	31.00
Ga	23.00	28.00	25.00	-	-	-	-	-
Pb	14.00	13.00	49.00	-	-	-	-	-
Rb	195.00	233.00	279.00	121.00	240.00	187.00	149.00	210.00
Sr	27.00	51.00	49.00	87.00	44.00	44.00	83.00	38.00
Th	17.00	16.00	16.00	12.20	14.10	10.80	-	11.20
Y	45.00	37.00	40.00	-	-	-	-	-

	4	4	4	4	4	4
Sample	39799	39800	39801	39802	39803	5198
SiO_2	69.76	65.55	69.32	62.82	73.98	70.70
TiO_2	0.79	0.72	0.62	0.86	0.75	0.42
Al_2O_3	13.24	15.29	14.22	17.36	11.81	12.90
Fe_2O_3	5.01	5.55	5.60	6.40	4.56	4.76
MgO	2.52	2.97	3.11	3.02	2.15	2.50
CaO	0.36	1.37	0.74	0.24	0.31	1.00
Na_2O	2.14	1.50	2.03	1.21	2.00	1.50
K_2O	2.57	3.93	2.68	4.94	2.51	2.70
P_2O_5	0.18	0.17	0.22	0.18	0.18	0.12
LOI	1.90	2.85	2.02	2.65	2.15	-
Total	98.47	99.90	100.56	99.68	100.40	96.60
Cr	80.00	82.00	71.00	98.00	63.00	-
Ba	411.00	564.00	404.00	726.00	347.00	-
La	46.20	-	33.40	41.90	35.80	-
Ce	68.20	61.00	58.60	77.40	69.10	-
Nd	38.00	36.00	29.00	41.00	45.00	-
Rb	125.00	178.00	124.00	243.00	121.00	-
Sr	68.00	88.00	67.00	29.00	52.00	-
Th	14.00	12.60	13.60	15.10	12.80	-

Table 2. Geochemical analyses of the Greenland Group and the Roaring Lion Formation. 1=Roaring Lion Formation, 2=Greenland Group, 3=Greenland Group (Smith, 1992), 4=Greenland Group (Nathan, 1976).



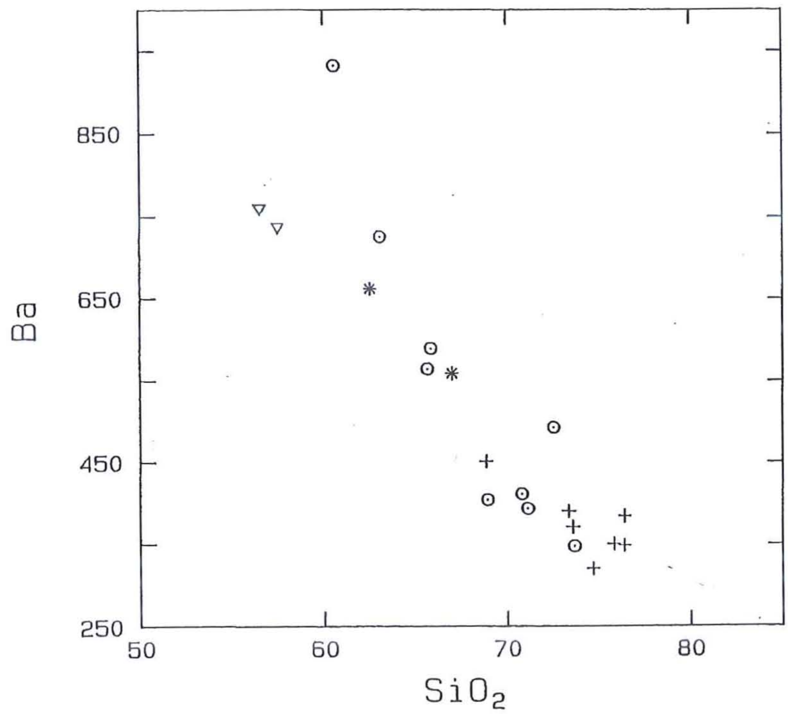


Fig.38. Al_2O_3 and Ba displaying a linear decline in abundance with increasing SiO_2. There is no significant difference between the Roaring Lion Formation and the Greenland Group in these plots. Symbols for the above and following plots: +Roaring Lion Formation, *Greenland Group, ʘ Greenland Group (Nathan, 1976),▿Greenland Group (Smith, 1992).

Av. values	**Greenland Group**	**Roaring Lion**
K_2O/Na_2O	2.78	1.29
CaO	0.78%	0.77%
Rb/Sr	3.65	1.85
SiO_2	67.43%	74.03%

(The enclaves plot well away from the Greenland Groups average composition and were excluded from the above calculations).

The Roaring Lion Formation has relatively less K_2O and more Na_2O causing the lower K_2O/Na_2O ratio (Fig.39). CaO is equally abundant in both rock units. The Rb/Sr ratios show the Roaring Lion Formation is relatively poor in Rb and rich in Sr.

Many authors have noted that a decrease in SiO_2 and Na_2O and an increase in K_2O occurs as sediment grain size decreases (eg Pettijohn 1957, Nathan 1976, and Roser and Korsch 1986). This is a result of less modal quartz, feldspar and lithic fragments and more modal matrix and phyllosilicates in finer grained rocks (Roser and Korsch, 1986). Because the Roaring Lion Formation is richer in quartz it has less K bearing mud derived matrix accounting for the low K_2O/Na_2O ratio. Furthermore Heier and Adam (1964) found most marine clays are enriched in Rb relative to sea water. Therefore the Roaring Lion formations relatively low Rb/Sr ratio also indicates it has a lower clay fraction than that of the Greenland Group (Fig.40).

However the issue is complicated somewhat by the composition of the source rock. Floyd and Leveridge (1987) show that K_2O and Rb abundances are dependant on source rock acidity. An acid to intermediate source is richer in K and Rb compared to a basic source.

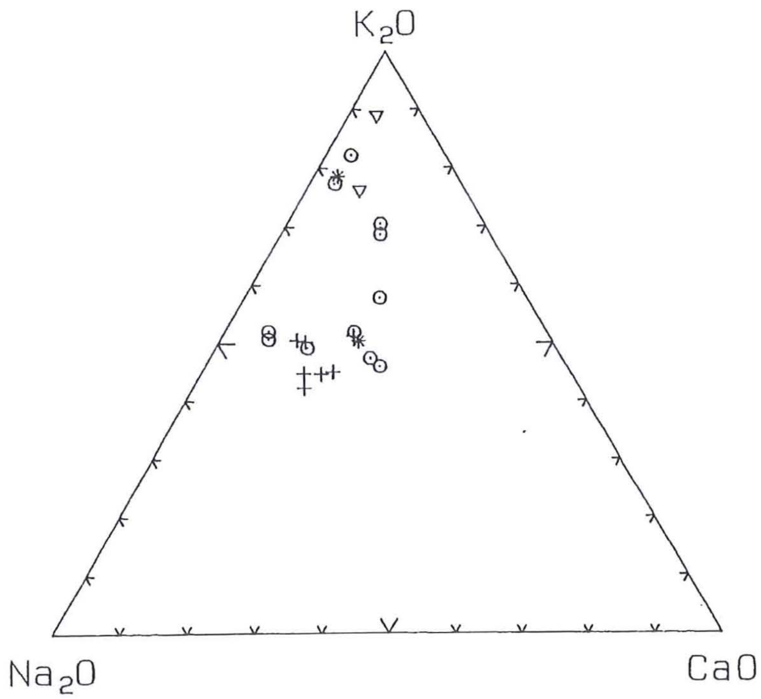


Fig.39. K_2O-Na_2O-CaO plot for the Greenland Group and Roaring Lion Formation, showing the Roaring Lion Formation has slightly less K_2O than the Greenland Group.

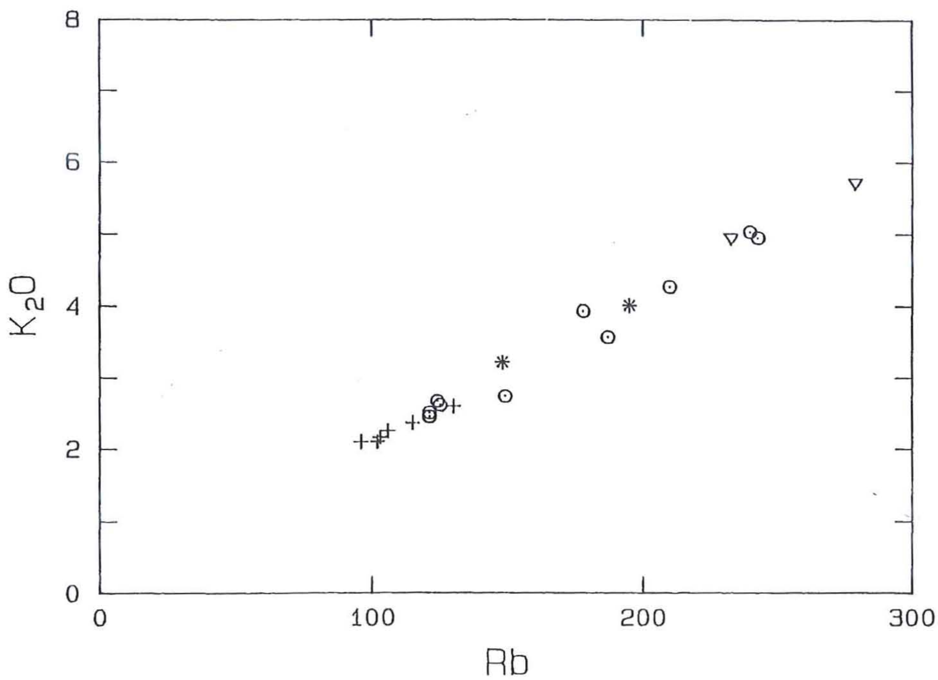


Fig.40. K_2O vs Rb. Linear decease in K_2O and Rb from the Greenland Group to the Roaring Lion Formation corresponds with a decrease in original clay content.

Both the Roaring Lion Formation and the Greenland Group plot well within the acid-intermediate source field. Figure 41 indicates that the Roaring Lion Formation had a more basic source than the Greenland Group. This does not account for the more mature Roaring Lion Formation which has been depleted in Rb and K during sedimentary reworking. Compensating for this loss of K and Rb would shift the Roaring Lion Formation up toward the acidic end of the source rock field where the Greenland Group plots. Therefore it is possible that the Roaring Lion Formation and the Greenland Group were sourced from the same acidic terrain.

PROVENANCE

Roser and Korsch (1986) defined three main tectonic provenances:

1) Passive Continental Margin (PM): basins on continental crust and basins associated with ocean floor spreading, failed rifts and Atlantic type continental margins.

2) Active Continental Margin (ACM): subduction related and continental collision basins.

3) Ocean Island Arc (ARC): subduction related basins.

The Greenland Group and Roaring Lion Formation plot within the passive margin field in keeping with their quartz rich evolved nature (Fig.42).

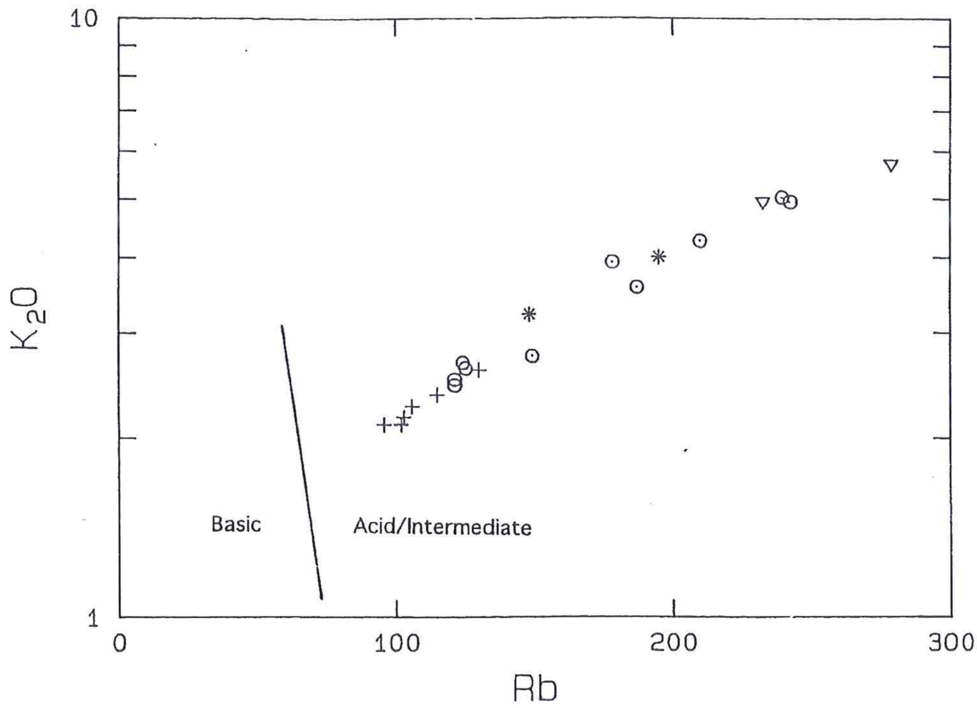


Fig.41. Distribution of K_2O (log%) and Rb with relation to source rock composition. Boundary line between acid/intermediate and basic composition after Floyd and Leveridge (1987).

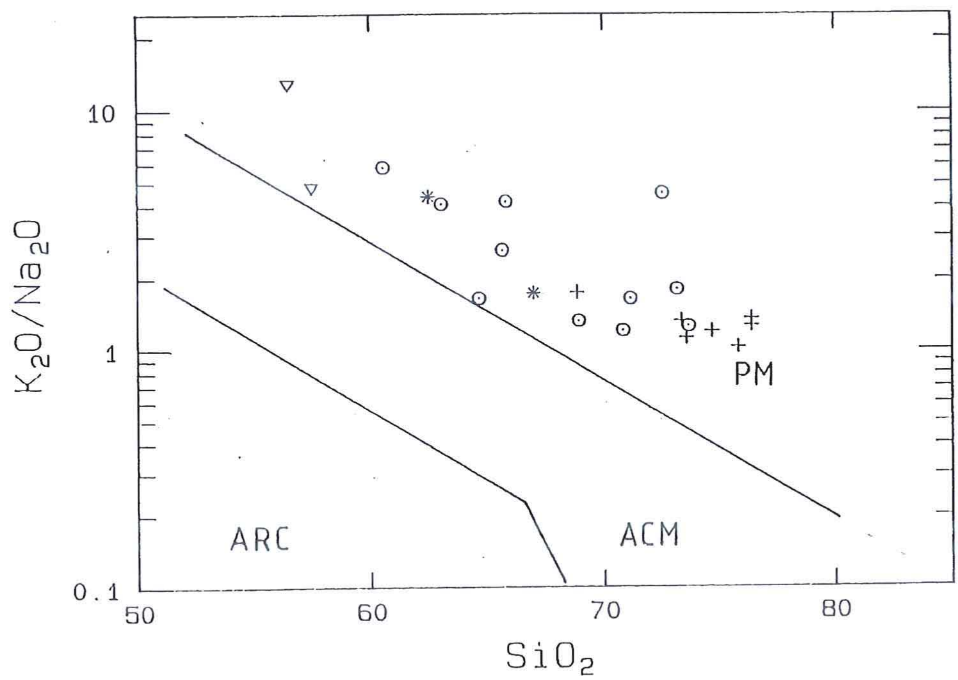


Fig.42. Tectonic discrimination diagram for sandstones and argillites after Roser and Korsch (1986). PM=Passive Margin, ARC=Oceanic Island Arc, and ACM=Active Continental Margin.

CONCLUSIONS

The Roaring Lion Formation is more mature than the Greenland Group containing relatively more SiO_2 and less K_2O and Rb. When this more mature nature of the Roaring Lion Formation is taken into account for it seems likely that the two rock units were sourced from the same terrain or two very similar ones. Reed (1957), Aronson (1968) and Laird (1972) also believe the Greenland Group was derived from a quartz rich terrain. High temperature polycrysalline quartz in the Roaring Lion Formation also indicates an acidic/plutonic source.

The strong geochemical similarity between the Roaring Lion Formation and the Greenland Group is supported by the similarities in sedimentary character (deep water turbidite deposits) and age (Lower Ordovician). It is very probable that the two units were deposited within the same sedimentary basin. Stronger correlation between the two units is justified, and possibly a review of the stratigraphic nomenclature. It is interesting to note that the Greenland Group contains no formations, unless the Roaring Lion and Webb Formations are included as suggested by Cooper (1989) and supported here.

CHAPTER SIX

ANATOKI THRUST

INTRODUCTION

The Anatoki Thrust defines the boundary between the Buller and Takaka terranes, and an understanding of its movement history is essential if the geological history of the region is to be revealed. Despite its obvious significance few papers have dealt with it, and then only briefly.

Grindley's Allochthonous Central Belt hypothesis (Grindley, 1961) requires the Anatoki Thrust to have originally been a low angle structure on which the Central Belt rocks were thrust northward. Later the Devil River-Anatoki thrust plane was folded into a synform, with associated reverse movement on the now east dipping thrust.

Brathwaite (1968) supported the Allochthonous Central Belt model, publishing evidence for northward thrusting adjacent to the Mount Olympus Pluton. He also maintained greenschist facies conditions were associated with thrusting.

Cooper (1979a) found no increase in metamorphism towards the thrust. He thought the movement history was complex but restricted mainly to the period from the Late Ordovician to Early Devonian. In later a paper Cooper thought docking of the Takaka and Buller terranes probably occurred in the earliest Devonian (Cooper, 1986), and a considerable component of strike slip movement was possible (Cooper, 1989).

Powell (1985) in his study of calc-mylonites within the Anatoki Thrust concluded that "*an episode of essentially dip-slip reverse movement* " is recorded in the rocks.

Finally, Rennison (1992) found evidence for Cretaceous normal faulting on the Anatoki "Thrust", adjacent to the Mt Olympus Pluton.

In summary, previous workers have proposed either northward thrusting, westward thrusting, strike slip, or normal movements on the Anatoki "Thrust". Here an attempt was made to determine the sense of movement on the Anatoki Thrust in the east of the field area where a deformed limestone is contained within the Anatoki Thrust Zone.

ROCKS WITHIN THE ANATOKI THRUST ZONE

A) FAULT BRECCIA

West of Kakapo Peak the Anatoki Thrust is marked by a 10 metre wide breccia zone (Fig.43). It is composed of limestone and volcanic rock fragments. The volcanic rock fragments are most likely to have been derived from the adjacent Devil River Volcanics, and contain large euhedral crystals which have been totally replaced by chlorite (Fig.44). The calcite represents Mount Patriarch Group limestone, and has been incorporated with the weathered volcanics in the fault breccia. Minor sulphide mineralisation was also noted in the breccia zone.

(B) DEFORMED MT PATRIARCH LIMESTONE

The Mount Patriarch Group occurs as a sliver in the Anatoki Thrust Zone. An oriented sample of Mount Patriarch Formation limestone was taken from the thrust zone west of Kakapo Peak. Here the Mount Patriarch Formation dips parallel to the Anatoki Thrust and is strongly deformed. An abundance of crinoid ossicles and shell fragments can still be recognised however.

Using the method of Turner (1953), "C" and "T" directions were estimated by orientation analyses of calcite c-axes and twins measured on a universal stage. The BASIC program CALCSTRESS (Shelley, 1989) was used to calculate the orientations of compression and

Fig.43. Fault breccia west of Kakapo Peak looking to the north. Hammer handle is 40cm long.

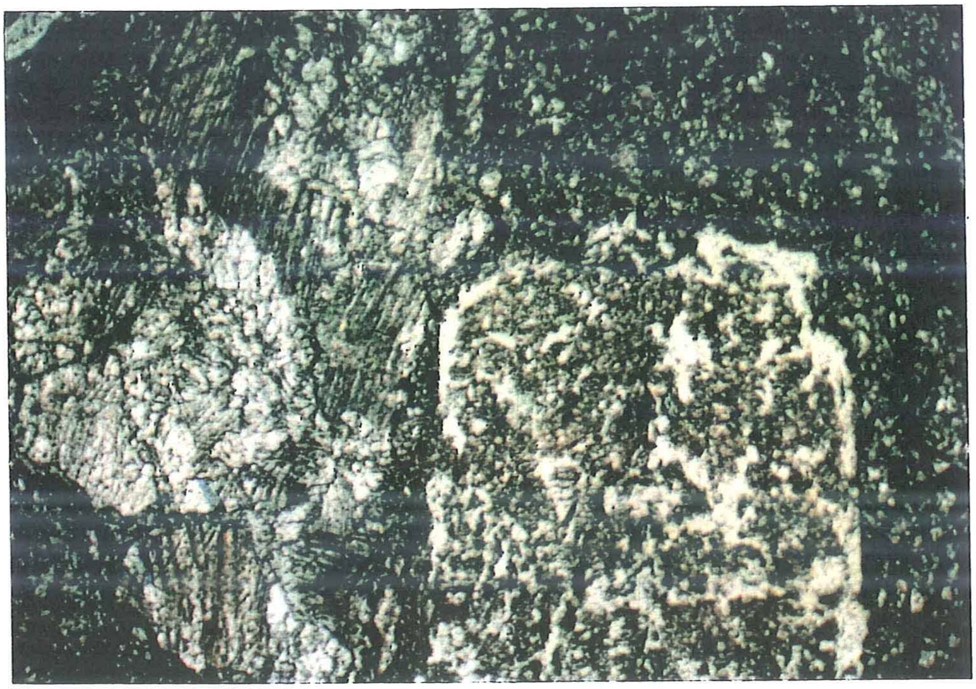


Fig.44. Photomicrograph of the fault breccia which marks the Anatoki Thrust. A large euhedral crystal which has been replaced by chlorite is contained within a rock fragment of the Devil River Volcanics. Calcite comprises a rock fragment of the Mt Patriarch Group. (Sample AT1). Mag.x10 Plain polars.

tension axes.

Figure 45 shows measured c-axis orientations in three perpendicular sections. The section parallel to the plane of the Anatoki Thrust and bedding (section 3) contains a high density of steeply plunging poles. In the other two sections poles plunge at low angles, and although the three diagrams are not identical there is a persistent preferred orientation of c-axes perpendicular to bedding and the Anatoki Thrust (Fig. 46).

Compression directions display a greater inconsistency between sections (Fig.47). Figure 48 illustrates the spread of compression maxima which plunge to the west and east.

Plots of poles to e twin lamellae (Fig.49) are of little importance but are consistent with c-axis orientations. Note that section 3 has a paucity of steeply plunging points. This represents a blind spot due to the inability of the universal stage to measure twin lamellae parallel to the thin section.

Tension data is commonly unrepresentative of σ_3 and is not included here. The ideal Turner tension direction lies so close to the c-axis (19^0) that the presence of a c-axis preferred orientation severely restricts the possible positions of σ_3 (Shelley, 1992).

INTERPRETATION

It is well established in the literature that c-axis preferred orientations predate the formation of compression axis preferred orientations. For example Turner and Weiss (1963) state "*...it is clear that the e lamellae are late structures superposed on grains that have already been oriented by some other means.*" (1963, p413). As a result, compression

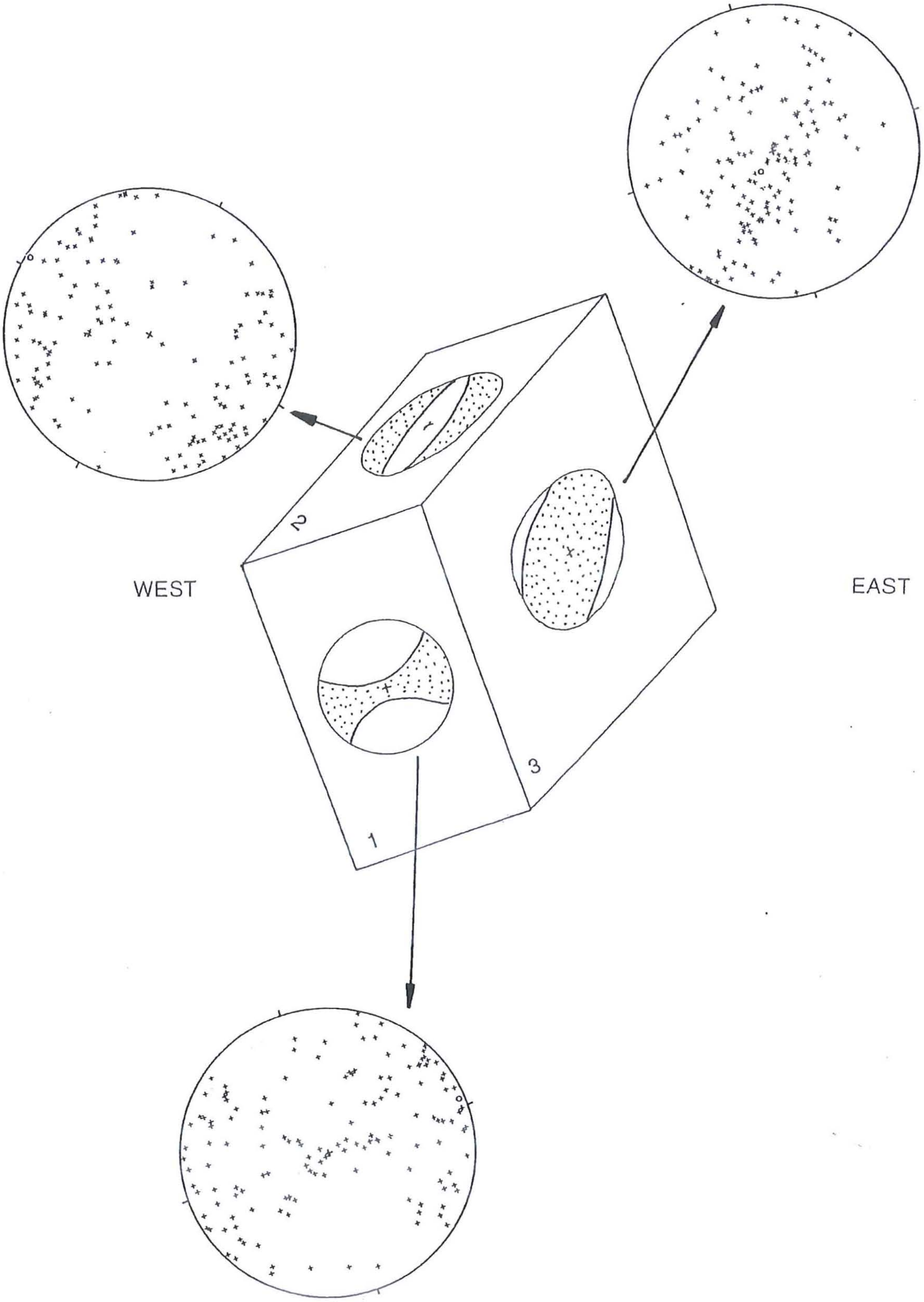


Fig.45. Plots of calcite c-axes in three perpendicular sections.

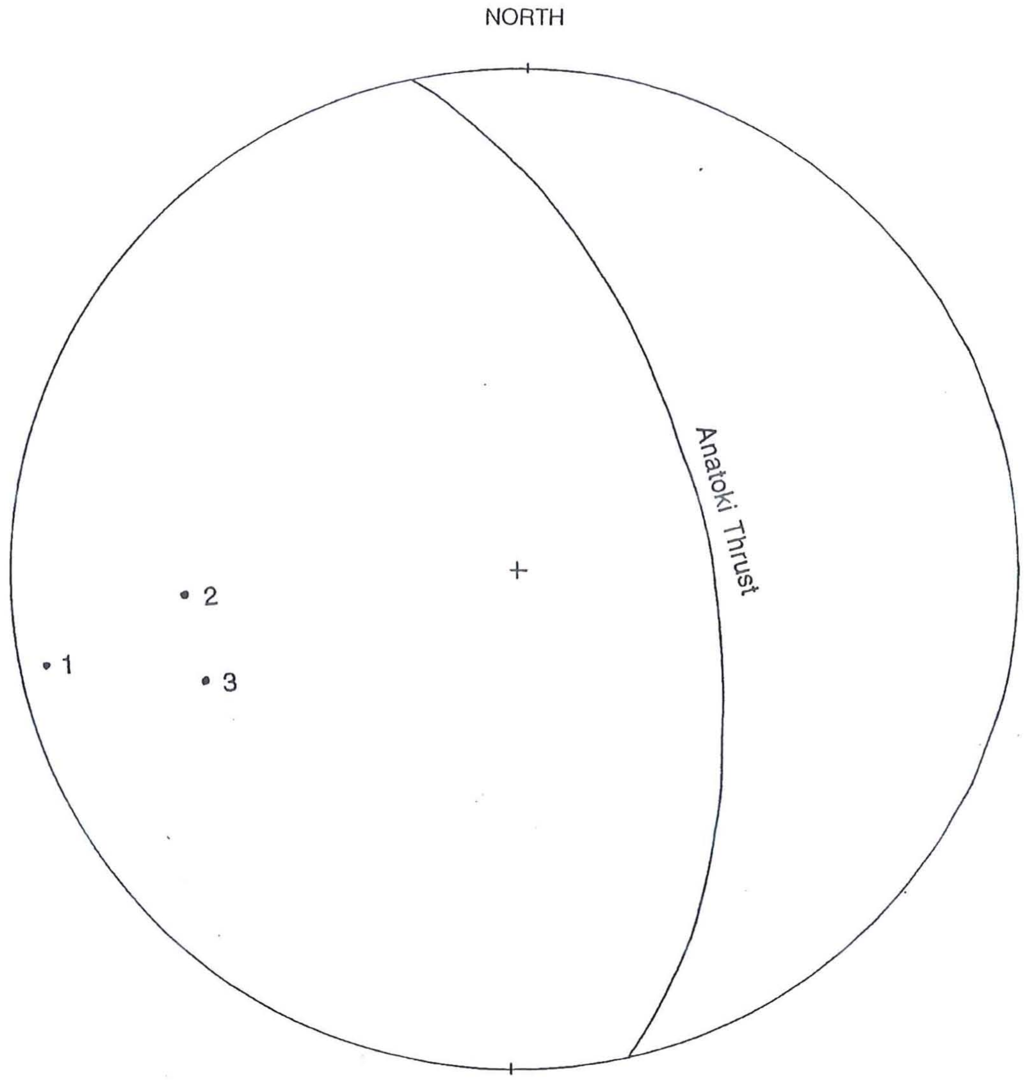


Fig.46. Measured c-axes maxima from the three sections rotated into a common horizontal plane. Numbers correspond to the sections in Fig.45, and the great circle represents the Anatoki Thrust.

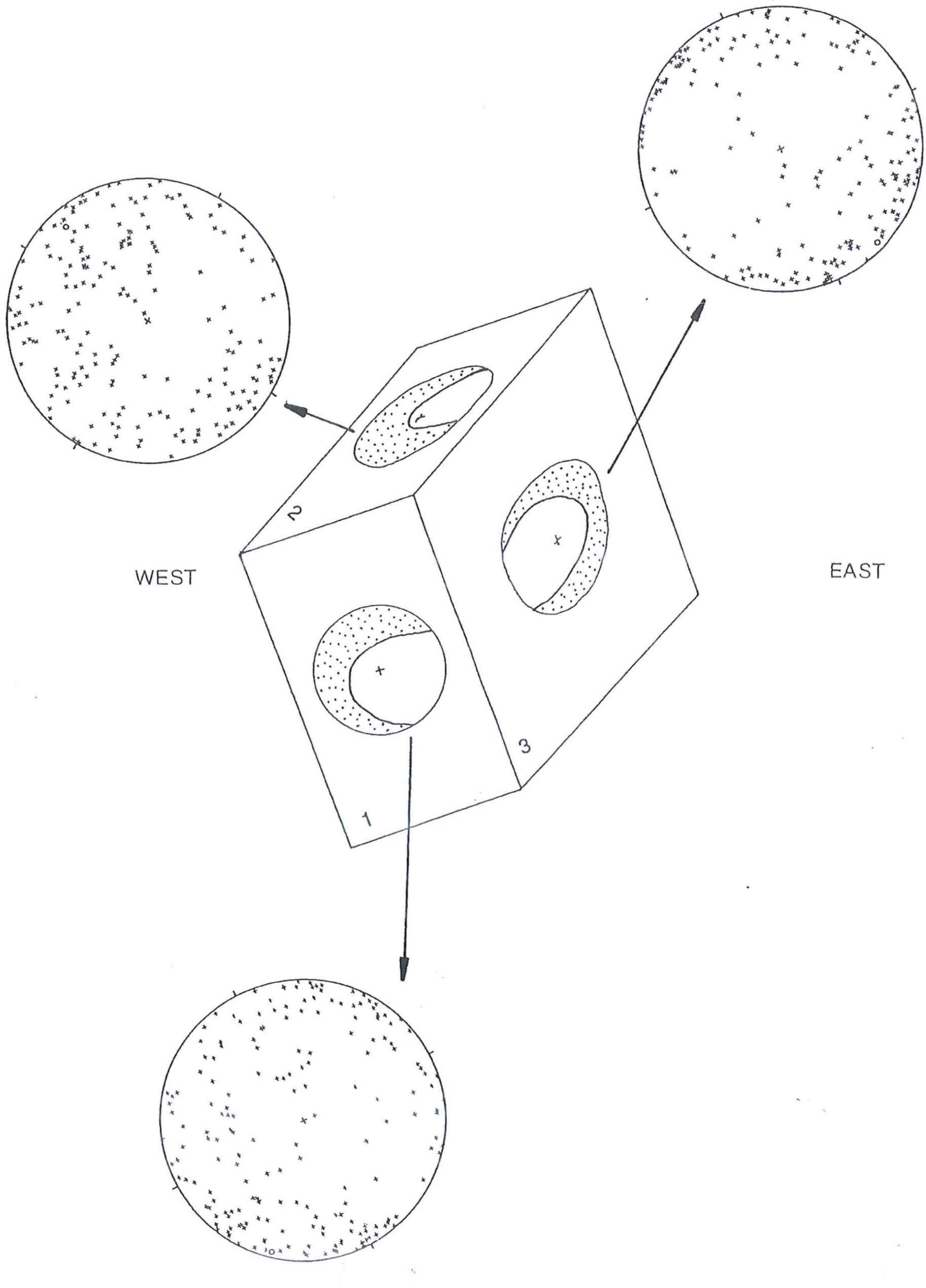


Fig.47. Plots of compression axes in three perpendicular sections.

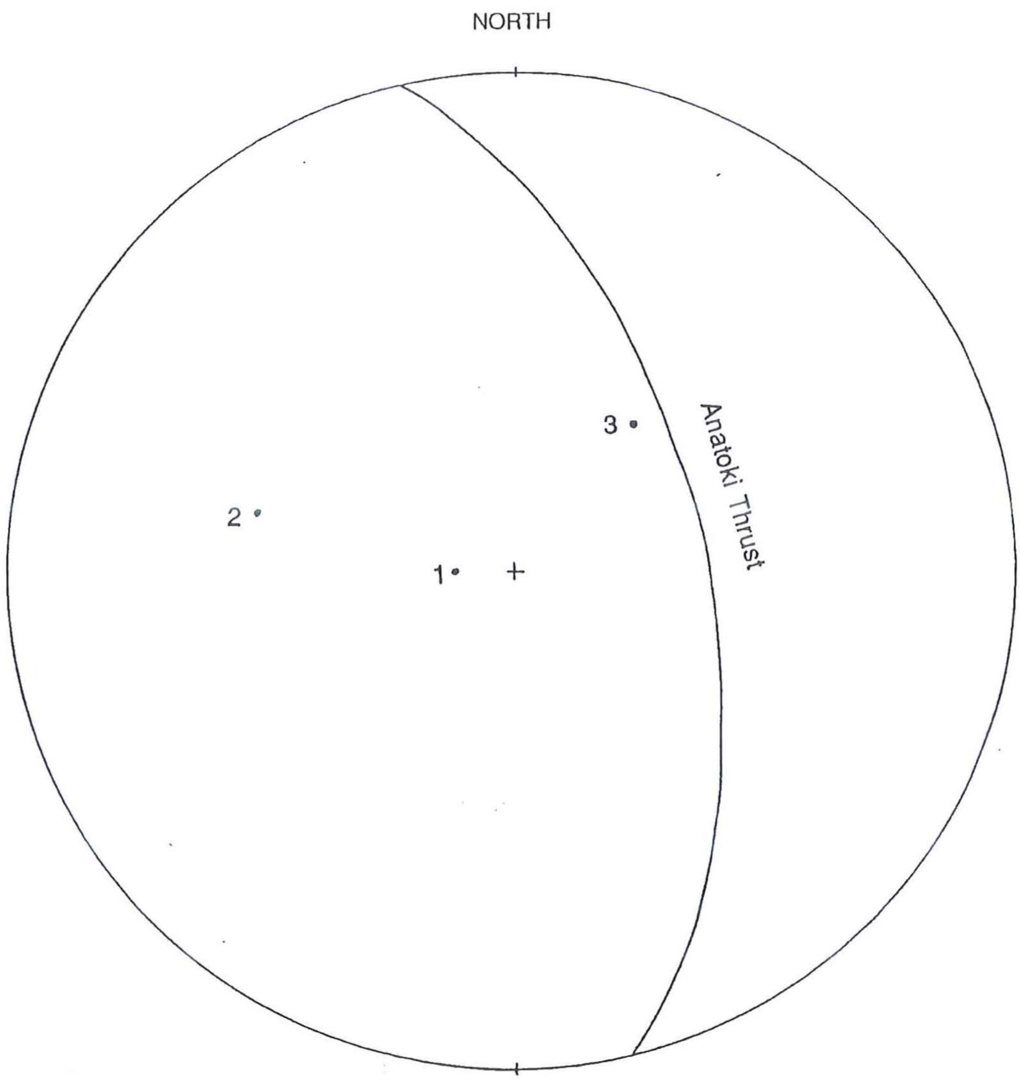


Fig.48. Measured compression maxima rotated into a common horizontal plane. Notation as for Fig.46.

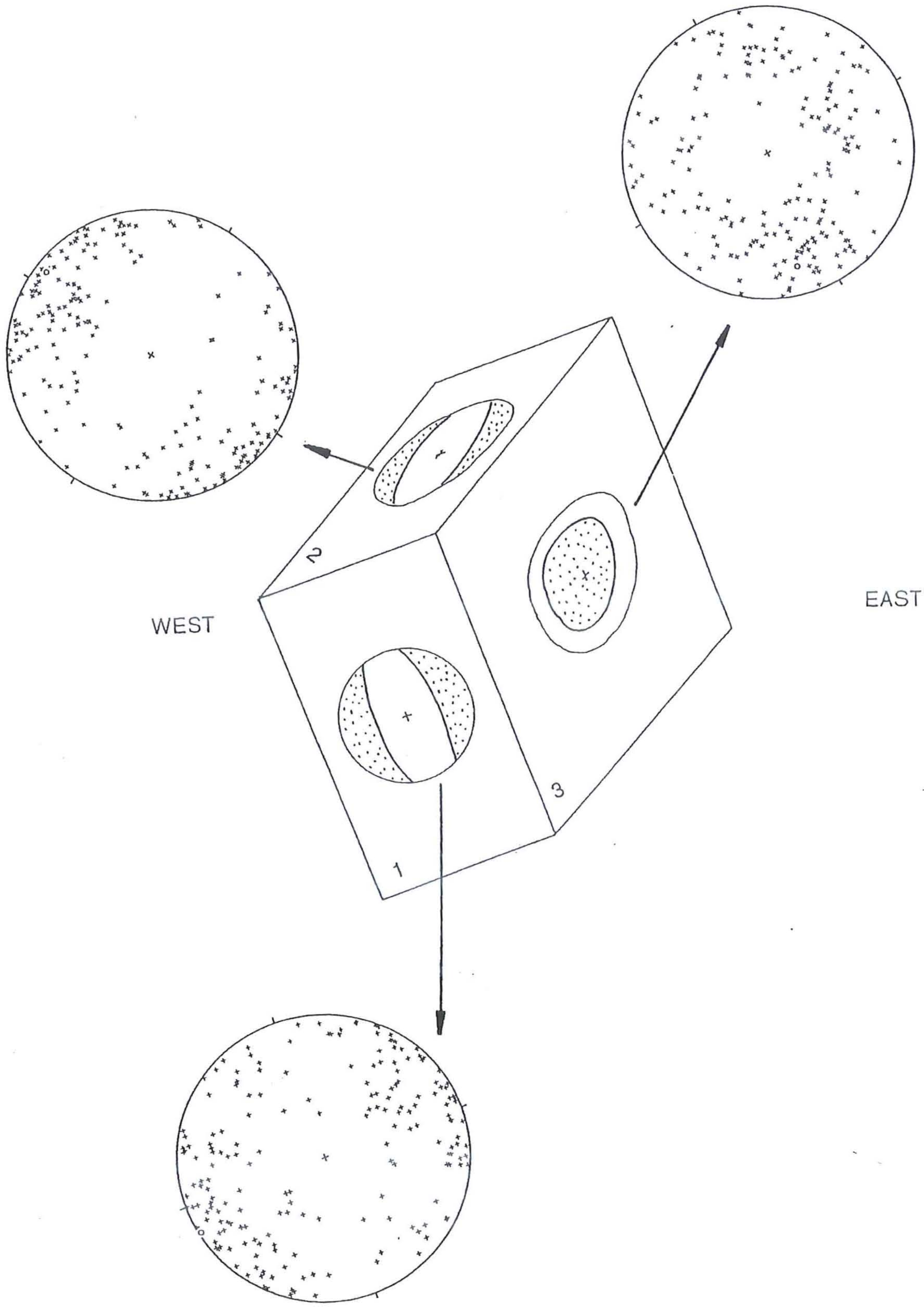


Fig.49. Poles to e twin lamellae.

axes commonly represent a final phase of deformation usually involving strain of small magnitude.

In uniaxial compression calcite develops a lattice preferred orientation with c-axes close to the shortening direction (eg Shelley, 1992 and Schmidt *et. al.*, 1987). Therefore the consistent orientation of c-axes perpendicular to bedding possibly indicates a period of compression perpendicular to bedding. However the presence of abundant crinoid ossicles also indicates the possibility that the lattice preferred orientation is of sedimentary origin.

Twinning of calcite and the associated compression axes postdated the c-axis preferred orientation. Figure 48 shows compression axes plunge at an angle greater than the dip of the Anatoki Thrust. This suggests the last movement on the east dipping Anatoki "Thrust" was normal (Fig.50).

Asymmetric calcite porphyroclast structures suggest an anticlockwise sense of rotation when viewed from the south; in agreement with Powell (1985) (Fig.51). This is inconsistent with the sense of movement indicated by compression axis orientations, but may possibly indicate an earlier phase of reverse movement on the fault. However the structures are not totally convincing.

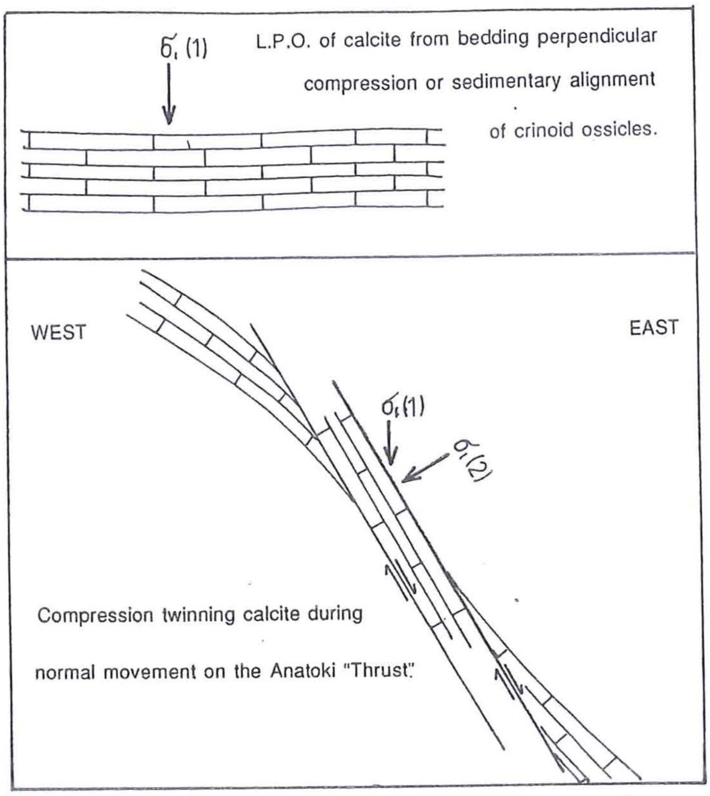


Fig.50. Origin of calcite twinning and c-axes preferred orientations.

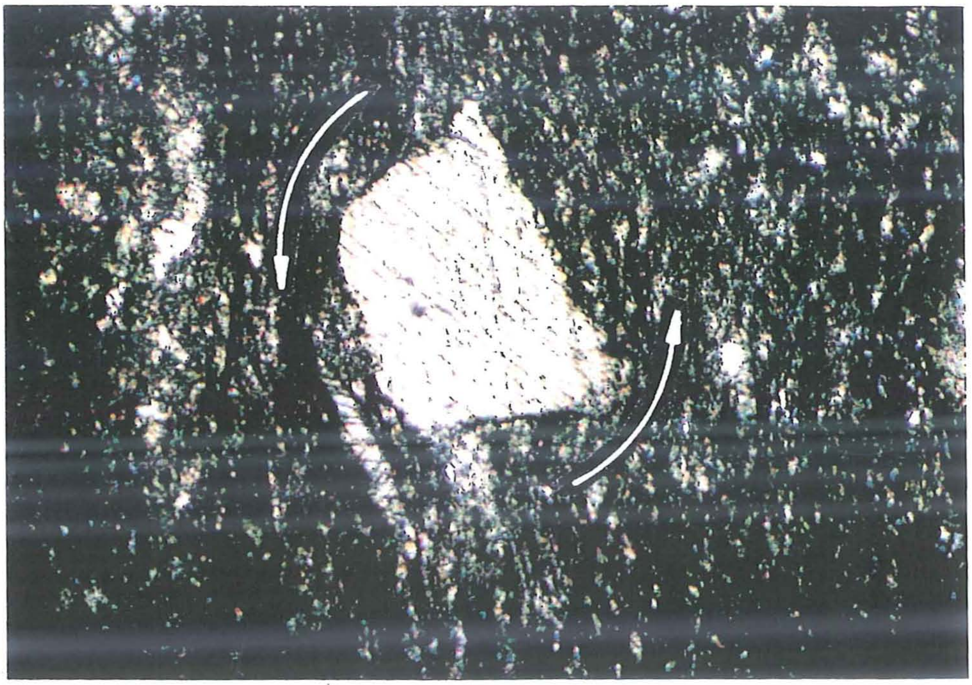


Fig.51. Calcite porphyroclast possibly indicating anticlockwise rotation as viewed from the south. (Sample SL1). Mag.x10 Crossed polars.

SUMMARY

To summarise the orientation of c-axes perpendicular to bedding indicates either

a) an initial phase of deformation with compression oriented perpendicular to bedding or

b) an original preferred orientation from the alignment of crinoid ossicles during sedimentation. Insufficient material was collected for these alternative ideas to be investigated further.

Asymmetric porphyroclast-type structure possibly indicate an early phase of reverse movement. These structures, and the c-axis preferred orientations are post dated by twinning which indicates normal movement on the Anatoki "Thrust".

More work is needed before this possible history of movement on the fault can be verified. However, with respect to the proposed late stage normal movement, Rennison (1992) also found evidence for normal movement post-dating the emplacement of the Mount Olympus Pluton. This adds weight to the suggestion that the last movement on the Anatoki "Thrust" was normal and which, according to the evidence of Rennison (1992), occurred in or after the Cretaceous.

CHAPTER SEVEN

CONCLUDING SUMMARY

The Buller terrane west of the Anatoki Thrust in Northwest Nelson comprises Ordovician marine sediments. They have strong similarities with the Ordovician sediments that occur at Aorangi Mine to the north of the field area, and are essentially lateral equivalents. The Aorangi Mine Formation which has its type section at Aorangi Mine is mapped within the Fenella Fault Zone at Cobb Valley following Cooper and Tullock (1992). The Roaring Lion Formation, Leslie Formation, and Douglas and Peel Formations of Cobb Valley are very similar to the Webb Formation, Slaty Creek Formation and Formation 'A' of Aorangi Mine respectively.

Structures in the field area have been divided into two domains. The first domain contains the Roaring Lion Formation which is folded by a deformation event associated with low greenschist facies metamorphism. This deformation is equated with the Silurian Greenland Tectonic Event of Cooper and Tullock (1992). The second domain contains cleavages which indicate a steeply plunging reclined fold similar to those described by Bishop (1968) and Grindley (1961, 1971, 1978 and 1980). Folding is likely to have resulted from reverse movement on the Anatoki Thrust.

Domains 1 and 2 were juxtaposed by the Fenella Fault Zone; a steeply dipping zone of bedding concordant faulting. Domain 1 contains deformation associated with a deeper structural level than Domain 2, and therefore it is inferred that the Fenella Fault Zone faulted Domain 1 up relative to Domain 2. Although it is now vertical the Fenella Fault Zone was probably originally a west dipping thrust.

Geochemistry shows the Roaring Lion Formation is slightly more mature than the Greenland Group, but otherwise very similar. It is highly probable that the Roaring Lion Formation and Greenland Group had the same source.

Calcite fabrics from marble at the Takaka-Buller terrane boundary indicate the last movement on the Anatoki "Thrust" was normal, and probably in the Cretaceous.

CHAPTER EIGHT

WORK TO BE DONE

The following points are possibilities for future work.

1) Detailed analysis and comparison of the Greenland Group, Roaring Lion Formation and Webb Formation.

2) Revision of the Douglas and Peel Formations stratigraphy.

3) Correlation of the Golden Bay Group with the Aorangi Mine Formation.

4) Detailed structural mapping along the Douglas and Peel Formations entire length.

5) Detailed structural analysis of rocks within the Fenella Fault Zone for its entire length.

6) Analysis of tectonites along the Anatoki Thrust.

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REFERENCES

ADAMS, C.J.D., HARPER, C.T. and LAIRD, M.G., 1975. K-Ar ages of low grade metasediments of the Greenland and Waiuta Groups in Westland and Buller, New Zealand. N.Z.J.G.G. **18(1)**: 39-48.

ARONSON, J.L., 1968. Regional geochronology of New Zealand. Geochim. et Cosmochim. Acta **32**: 669-697.

BELL, J.M., 1906. The Geology of the Hokitika Sheet, North Westland Quadrangle. N.Z.G.S. Bull. **1**: 101pp

BELL, J.M., WEBB, E.J.H. and CLARKE, E.D., 1907. The Geology of the Parapara Subdivision, Karamea, Nelson. N.Z.G.S. Bull. **3**: 111pp.

BENSON, W.N., 1956. Cambrian Rocks and Fossils in New Zealand (Preliminary Note). Pub. 20th Int. Geol. Congress, Mexico City **2(2)**: 285-288.

BISHOP, D.G., 1968a. Sheet S2 Kahurangi (1st ed.) "Geological map of New Zealand 1:63 360." DSIR, Wellington.

BISHOP, D.G., 1968b. Reclined folds and coaxial refolding in the Paleozoic rocks of North-west Nelson. N.Z.J.G.G. **11**: 593-607.

BISHOP, D.G., 1972. Progressive metamorphism from prehnite-pumpellyite to greenschist facies in the Dansey Pass area, Otago, New Zealand. Geol. Soc. Am. Bull. **83**: 3177-3197.

BISHOP, D.G., BRADSHAW, J.D. and LANDIS, C.A., 1985. Provisional terrane map of South Island, New Zealand. In D.G. Howell (ed.): "Tectonostratigraphic Terranes of the Circum-Pacific Region." Circum-Pacific Council for Energy and Mineral Resources, Earth Science Series **1**: 515-521.

REFERENCES

ADAMS, C.J.D., HARPER, C.T. and LAIRD, M.G., 1975. K-Ar ages of low grade metasediments of the Greenland and Waiuta Groups in Westland and Buller, New Zealand. N.Z.J.G.G. 18(1): 39-48.

ARONSON, J.L., 1968. Regional geochronology of New Zealand. Geochim. et Cosmochim. Acta 32: 669-697.

BELL, J.M., 1906. The Geology of the Hokitika Sheet, North Westland Quadrangle. N.Z.G.S. Bull. 1: 101pp

BELL, J.M., WEBB, E.J.H. and CLARKE, E.D., 1907. The Geology of the Parapara Subdivision, Karamea, Nelson. N.Z.G.S. Bull. 3: 111pp.

BENSON, W.N., 1956. Cambrian Rocks and Fossils in New Zealand (Preliminary Note). Pub. 20th Int. Geol. Congress, Mexico City 2(2): 285-288.

BISHOP, D.G., 1968a. Sheet S2 Kahurangi (1st ed.) "Geological map of New Zealand 1:63 360." DSIR, Wellington.

BISHOP, D.G., 1968b. Reclined folds and coaxial refolding in the Paleozoic rocks of North-west Nelson. N.Z.J.G.G. 11: 593-607.

BISHOP, D.G., 1972. Progressive metamorphism from prehnite-pumpellyite to greenschist facies in the Dansey Pass area, Otago, New Zealand. Geol. Soc. Am. Bull. 83: 3177-3197.

BISHOP, D.G., BRADSHAW, J.D. and LANDIS, C.A., 1985. Provisional terrane map of South Island, New Zealand. In D.G. Howell (ed.): "Tectonostratigraphic Terranes of the Circum-Pacific Region." Circum-Pacific Council for Energy and Mineral Resources, Earth Science Series 1: 515-521.

BRADSHAW, J.D., 1982. S13-Cobb: a review of the map and the structural interpretation of the Central Belt rocks of S13 and S8. N.Z.J.G.G. **25**: 371-379.

BRADSHAW, J.D., 1992. Do we need a Greenland Event? N.Z. Tectonics Study Group Newsletter **7**: 9.

BRATHWAITE, R.L., 1968. The geology of the Boulder Lake area, Northwest Nelson. Part 1-The Anatoki Formation. N.Z.J.G.G. **11**: 78-91.

COOPER, R.A., 1974. Age of the Greenland and Waiuta Groups, South Island, New Zealand. N.Z.J.G.G. **17**: 995-962.

COOPER, R.A., 1979a. Lower Paleozoic rocks of New Zealand. J.R.S.N.Z. **9**: 29-84.

COOPER, R.A., 1979b. Ordovician geology and graptolite faunas of the Aorangi Mine area, North west Nelson, New Zealand. N.Z.Geol.Survey Paleontological Bull. **47**: 137pp.

COOPER, R.A., 1986. A terrane interpretation of the early evolution of New Zealand. Lower Paleozoic Workshop Abstracts, Geol. Soc. N.Z., Misc. Pub. **34**: 14-16.

COOPER, R.A., 1989. Early Paleozoic terranes of New Zealand. J.R.S.N.Z. **19**: 73-112.

COOPER, R.A. and GRINDLEY, G.W. (eds.), 1982. Late Proterozoic to Devonian sequences of southeastern Australia, Antarctica, and New Zealand. Geol. Soc. Aus. Spec. Pub. **9**: 103pp.

COOPER, R.A. and TULLOCK, A.J., 1992. Early Palaeozoic terranes in New Zealand and their relationship to the Lachlan Fold Belt. Tectonophy. **214**: 129-144.

COX, S.H., 1882. District between the Aorere and Takaka Valleys, Collingwood. N.Z.G.S. Reps. of Geol. Expl. **15**: 42-56.

FLEUTY, M.J., 1964. The description of folds. Proc. Geol. Assoc. **75**: 461-89.

FLOYD, D.A. and LEVERIDGE, B.E., 1987. Tectonic environment of the Devonian Gramscatho basin, south Cornwall: framework mode and geochemical evidence from turbiditic sandstones. J. Roy. Soc. Lond. **144**: 531-542.

FOLK, R.L., ANDREWS, P.B. and LEWIS, D.W.,1970. Detrital sedimentary rock classification and nomenclature for use in New Zealand. N.Z.J.G.G. **13**: 937-968.

GRINDLEY, G.W., 1961. Sheet 13-Golden Bay (1st ed.). "Geological Map of New Zealand 1:250 000." DSIR, Wellington, New Zealand.

GRINDLEY, G.W., 1971. Sheet S 8-Takaka (1st ed.). "Geological Map of New Zealand, 1:63 360." DSIR, Wellington, New Zealand.

GRINDLEY, G.W., 1978. Chapter III. Tectonism of the early geosynclinal cycle: the Tuhua Orogeny and the New Zealand Geanticline. In Suggate, R.P., Stevens, G.R. and Te Punga, M.T. (eds.). "The Geology of New Zealand Vol. 1." Government Printer, Wellington. 343pp.

GRINDLEY, G.W., 1980. Sheet S13-Cobb (1st ed.) "Geological Map of New Zealand 1:63 360." DSIR, Wellington, New Zealand.

GRINDLEY, G.W., 1982. S 13-Cobb. A review of the new map and the structural interpretation of the Central Belt rocks of S 13 and S 8-Reply. N.Z.J.G.G. **25**: 371-379.

HEIER, K.S. and ADAMS, J.A.S., 1964. The geochemistry of the alkali metals. in Ahrens, L.H., Press, F. and Runcorn S.K. (eds.) "Physics and chemistry of the earth v5." MacMillian, New York.

HENDERSON, J., 1917. The Geology and Mineral Resources of the Reefton Subdivision. N.Z.G.S. Bull. 18.

KEBLE, R.A. and BENSON, W.N., 1929. Ordovician Graptolites of North-west Nelson. Trans. of the N.Z. Inst. 56: 840-863.

LAIRD, M.G., 1972. Sedimentology of the Greenland Group in the Paparoa Range, West Coast, South Island. N.Z.J.G.G. 15: 372-393.

LEWIS, D.W., 1984. Practical Sedimentology. University of Canterbury, New Zealand. 229pp.

McKAY, A., 1879. The Baton River and Wangapeka districts and Mount Arthur Range. N.Z.G.S. Reps. of Geol. Expl. 12: 123-5.

MORGAN, P.G., 1908. The geology of the Mikonui Subdivision, North Westland. N.Z.G.S. Bull. 13: 159pp.

NATHAN, S., 1976. Geochemistry of the Greenland Group (early Ordovician), New Zealand. N.Z.J.G.G. 19: 683-706.

NORRISH, K. and HUTTON, J.T., 1969. An accurate X-ray spectrographic method for the analysis of a wide range of geological samples. Geochim. et Cosmochim. Acta 33: 431-454.

PARK, J., 1890. On the Geology of Collingwood County, Nelson. N.Z.G.S. Reps. of Geol. Expl. 20: 186-243.

PARK, J., 1910. The Geology of New Zealand. Whitcombe and Tombs Limited.

PETTIJOHN, F.J., 1957. Sedimentary Rocks (2nd ed.). Harper, New York.

POTTER, P.E., MAYNARD, J.B. and PRYOR, W.A., 1980. Sedimentology of Shale. Study guide and reference source. Sringer-Verlag, New York. 303pp.

POWELL. N.G., 1984. Metamorphism within a part of the Waingaro Schist Zone, Northwest Nelson, New Zealand. MSc. Thesis, Auckland University.

POWELL, N.G., 1985. Devil River Fault and Anatoki Thrust: Their associated structures, mechanisms and senses of movement. Geol. Soc. N.Z., Misc. Pub. **32a**: 70.

RAMSAY, J.G., 1967. Folding and Fracturing of rocks. McGraw-Hill, New York. 568pp.

REED, J.J., 1957. Petrology of the Lower Mesozoic rocks of the Wellington District. N.Z.G.S. Bull. **57**: 60pp.

RENNISON, M.W., 1992. The Petrology, Structure and Geochemistry of the eastern margin of the Mount Olympus Pluton, Northwest Nelson, New Zealand. Unpublished BSc(Hons) Thesis, University of Canterbury. 58pp.

ROSER, B.P. and KORSCH, R.J., 1986. Determination of tectonic setting of sandstone-mudstone suites using SiO_2 content and K_2O/Na_2O ratio. J. Geol. **94**: 635-650.

SCHMIDT, S.M., PANOZZO, R. and BAUER, S., 1987. Simple shear experiments on calcite rocks: rheology and microfabric. J. Struct. Geol. **9**: 747-778.

SHELLEY, D., 1989. Calcstress: a program that calculates compression and tension directions from calcite U-stage data. Computers and Geosciences **15**: 269-273.

SHELLEY, D., 1992. Igneous and Metamorphic rocks under the microscope. Classification, textures, microstructures and mineral preferred orientations. Chapman and Hall, London. 445pp.

SKWARKO, S.K., 1960. The geology of the upper Cobb Valley with special reference to graptolite fauna. Unpublished MSc Thesis, Victoria University, Wellington.

SKWARKO, S.K., 1962. Graptolites of Cobb River-Mount Arthur area, Northwest Nelson, New Zealand. Trans. Roy. Soc. N.Z., Geology **1(5)**:215-247.

SMITH, J.B., 1992. The geochemistry, petrology and structure of granites from Cape Foulwind, southwest Nelson, New Zealand. Unpublished BSc (Hons) Thesis, University of Canterbury. 76pp.

TURNER, F.J., 1935. Metamorphism of the Te Anau Series in the region north-west of Lake Wakatipu. Roy. Soc. New Zealand. Trans. **65**: 329-349.

TURNER, F.J., 1953. Nature and dynamic interpretation of deformation lamellae in calcite of three marbles. Am. J.Sci. **251**: 276-298.

TURNER, F.J. and WEISS, L.E., 1963. Structural analysis of metamorphic tectonites. McGraw Hill, New York. 545pp.

APPENDIX ONE
ROARING LION FORMATION POINT COUNT DATA

	RLF2	RLF6	RLF7
MINERAL (vol%)			
Quartz	13.6	35.6	25.3
Albite	2.1	2.3	2.1
Muscovite	4.1	2.1	7.6
Chlorite	0.1	0	0.9
Iron	8.3	5.2	0.5
Opaques	0.7	0	0.3
ROCK FRAGMENTS	1.9	3.8	1.0
RECRY.MATRIX	69.2	51.0	62.3
TOTAL	**100**	**100**	**100**
POINTS COUNTED	550	550	550

APPENDIX TWO
SAMPLES

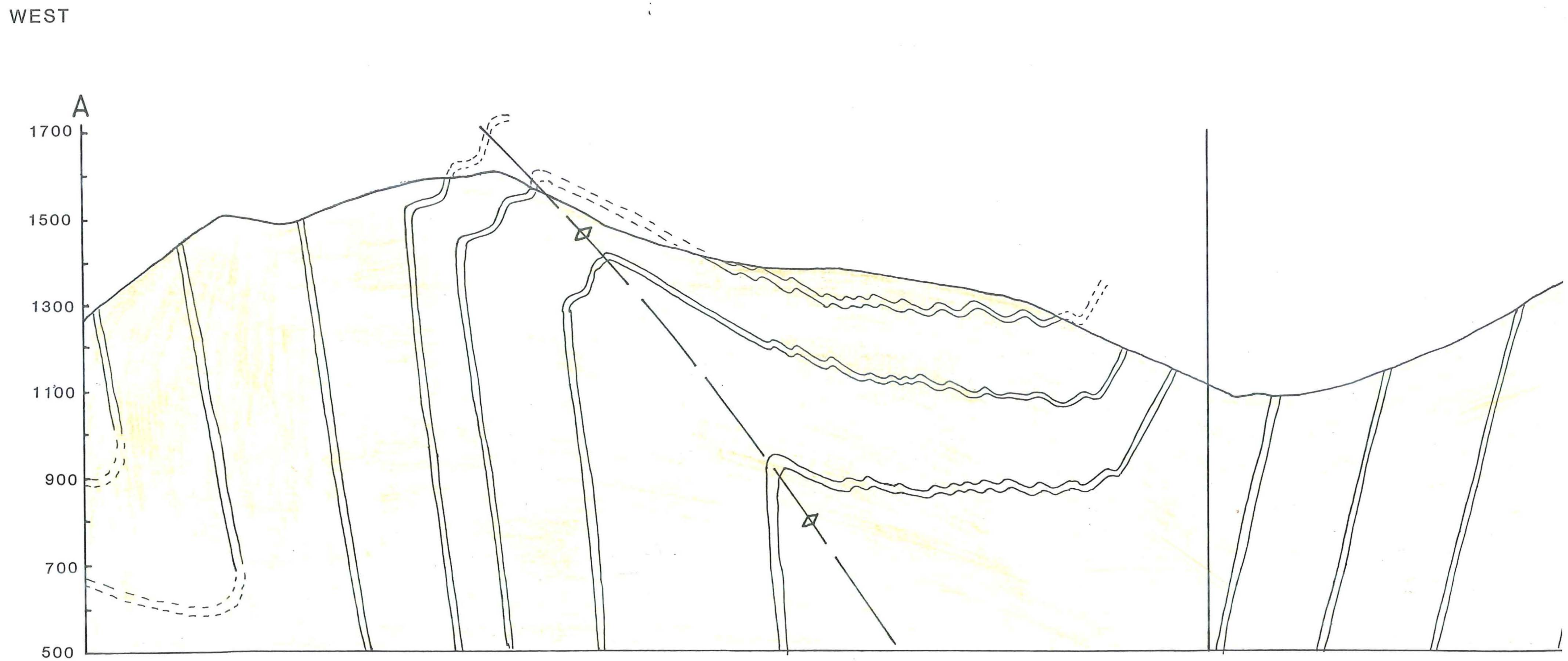
Grid references refer to NZMS 260 Sheet M26, Cobb.
TS=Thin section, XRF= Sample used for geochemical analysis.

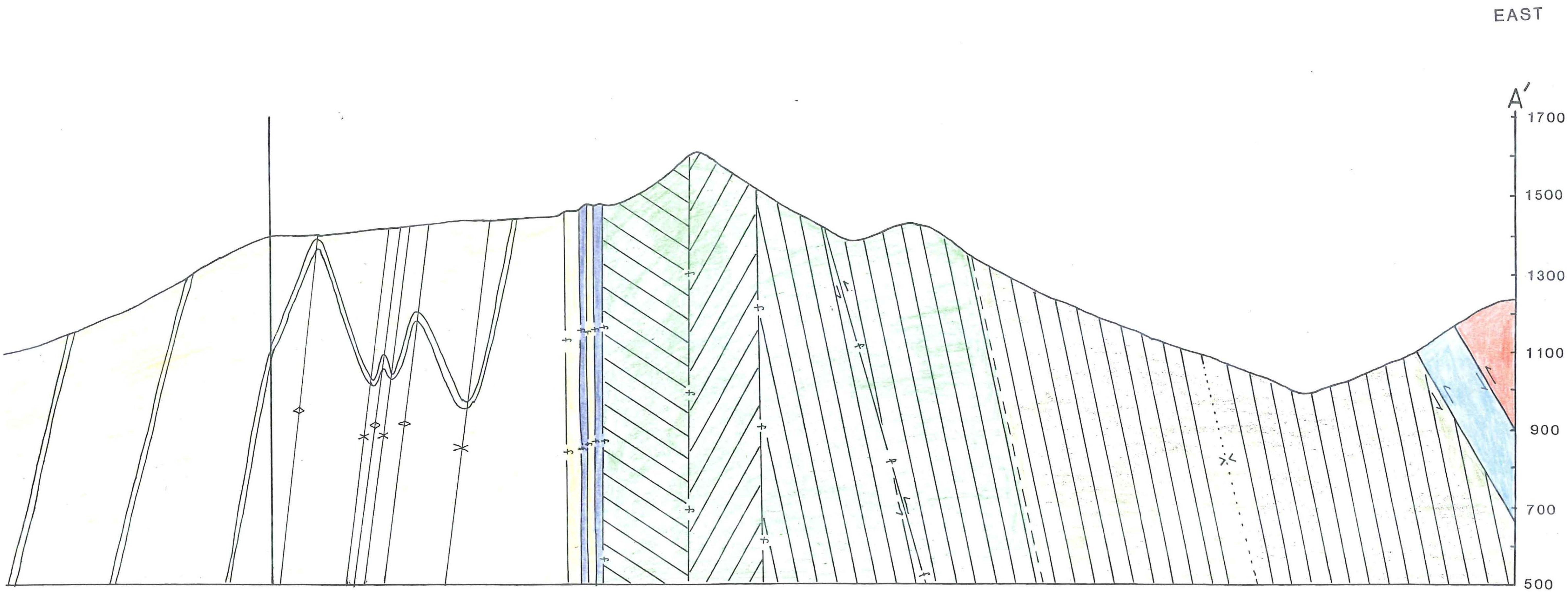
SAMPLE NAME	ROCK UNIT	SAMPLE TYPE	LOCATION
RLF6	Roaring Lion	TS	700173
RLF2	Roaring Lion	TS	684174
RLF7	Roaring Lion	TS	698176
LQ3c	Aorangi Mine	TS	706182
KP3*	Douglas Fm.	TS	719190
KP7	Peel Fm.	TS	723204
SL1	Mt. Patriarch	TS	723205
AT1	Fault Breccia	TS	727205
24686	Roaring Lion	XRF	700173
24687	Roaring Lion	XRF	698177
24688	Roaring Lion	XRF	697174
24689	Roaring Lion	XRF	698173
24690	Roaring Lion	XRF	698172
24691	Roaring Lion	XRF	697170
24692	Roaring Lion	XRF	702165
24693	Greenland Gp.	XRF	14 Mile Bluff
24694	Greenland Gp.	XRF	Globe Progress

* Borrowed by kind permission from Aaron Stallard (Geology Department, University of Canterbury).

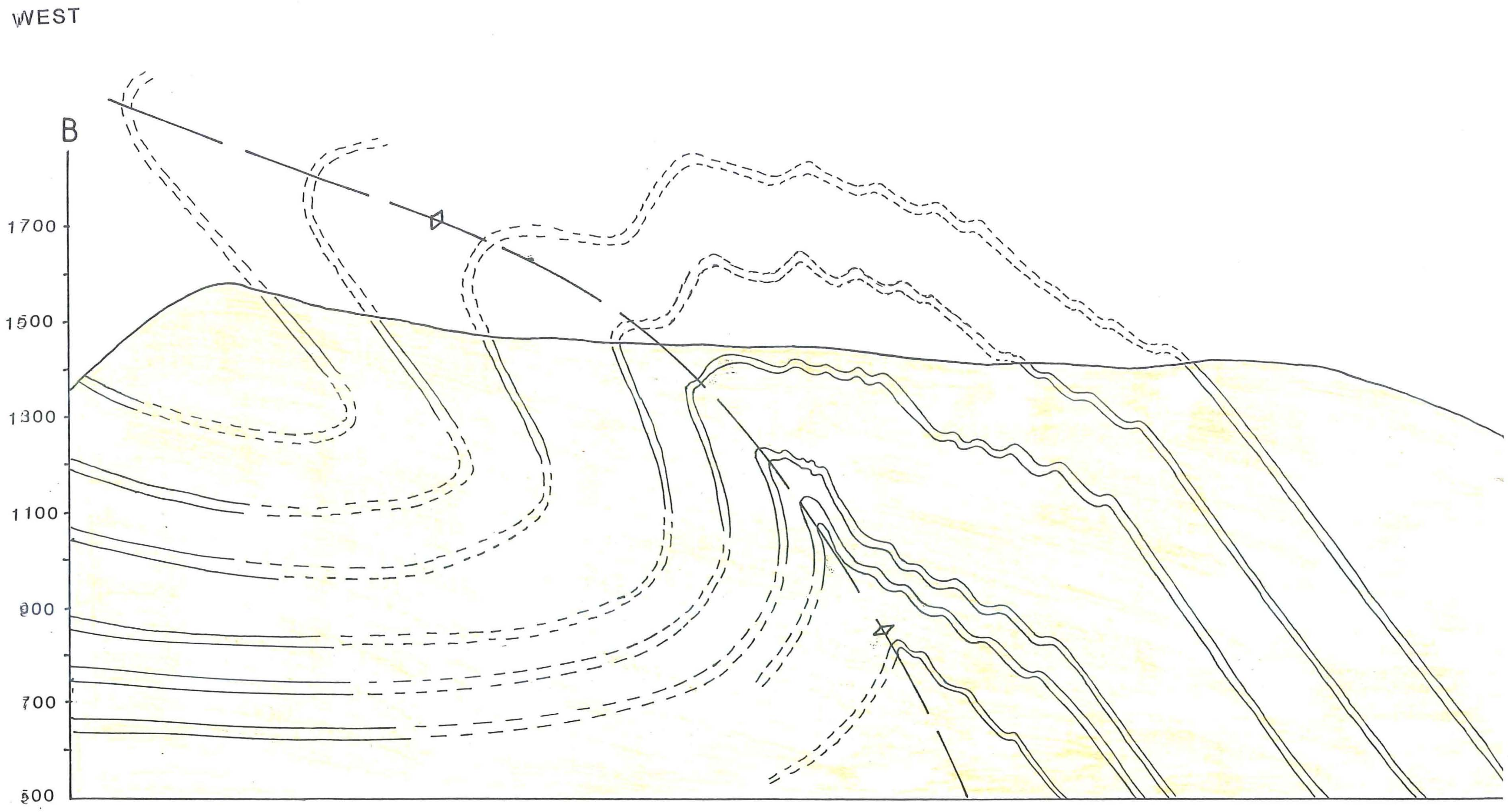
SECTION A–A´

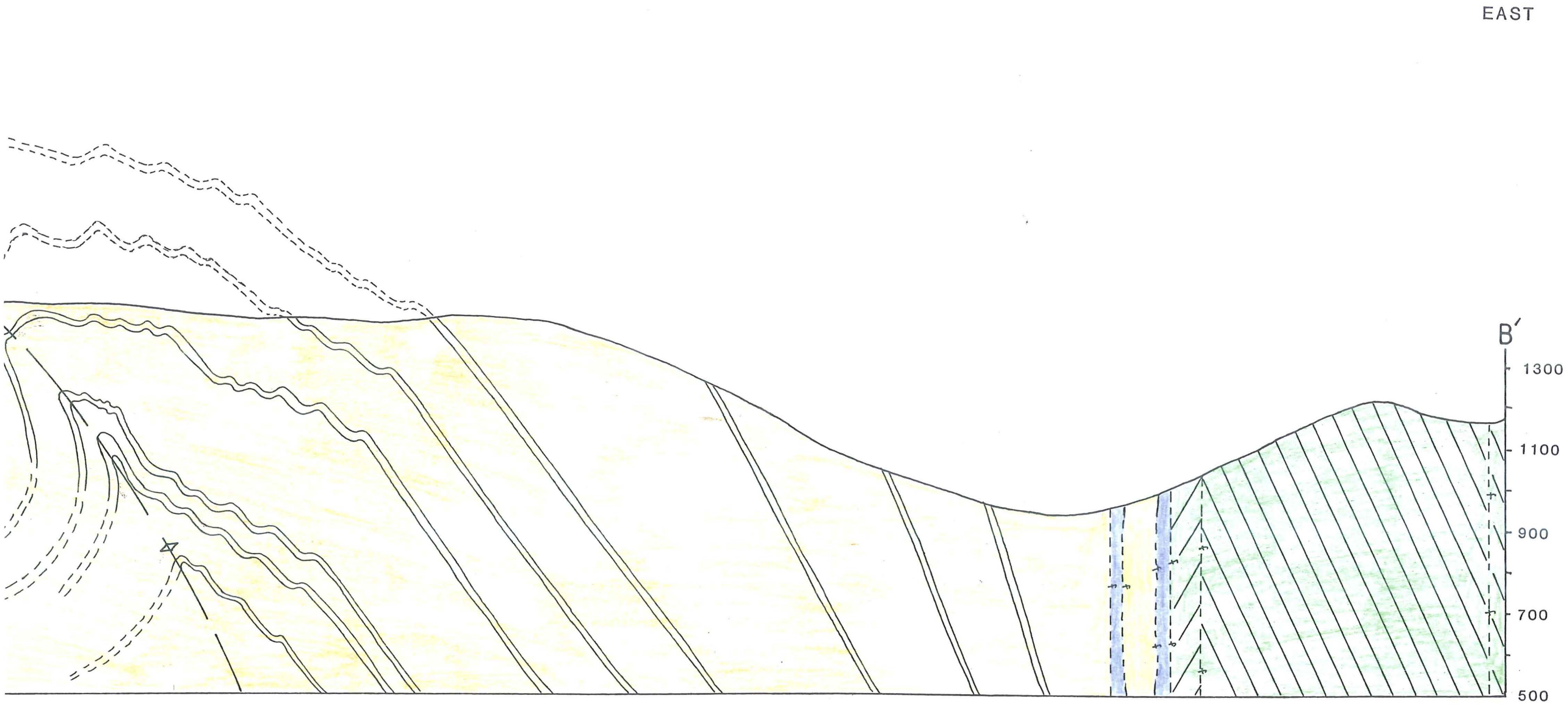
Scale 1:10 000 V=H




EAST
A′
1700
1500
1300
1100
900
700
500

SECTION B-B'




EAST
B′
1300
1100
900
700
500

LEGEND

- Undifferentiated Douglas and Peel Fms.
- Leslie Fm.
- Slate } Aorangi Mine Fm.
- Quartzite } Aorangi Mine Fm.
- Roaring Lion Fm.
- Fault Shear Zone
- Undifferentiated Patriarch and Summit Limestone Fms.
- Central Belt

GEOL

Bedding

Facing direction de

Facing direction no

Cleavage

Joints [

Observed

Contacts

Faults

Folds Syncline

Anticline

Monocline

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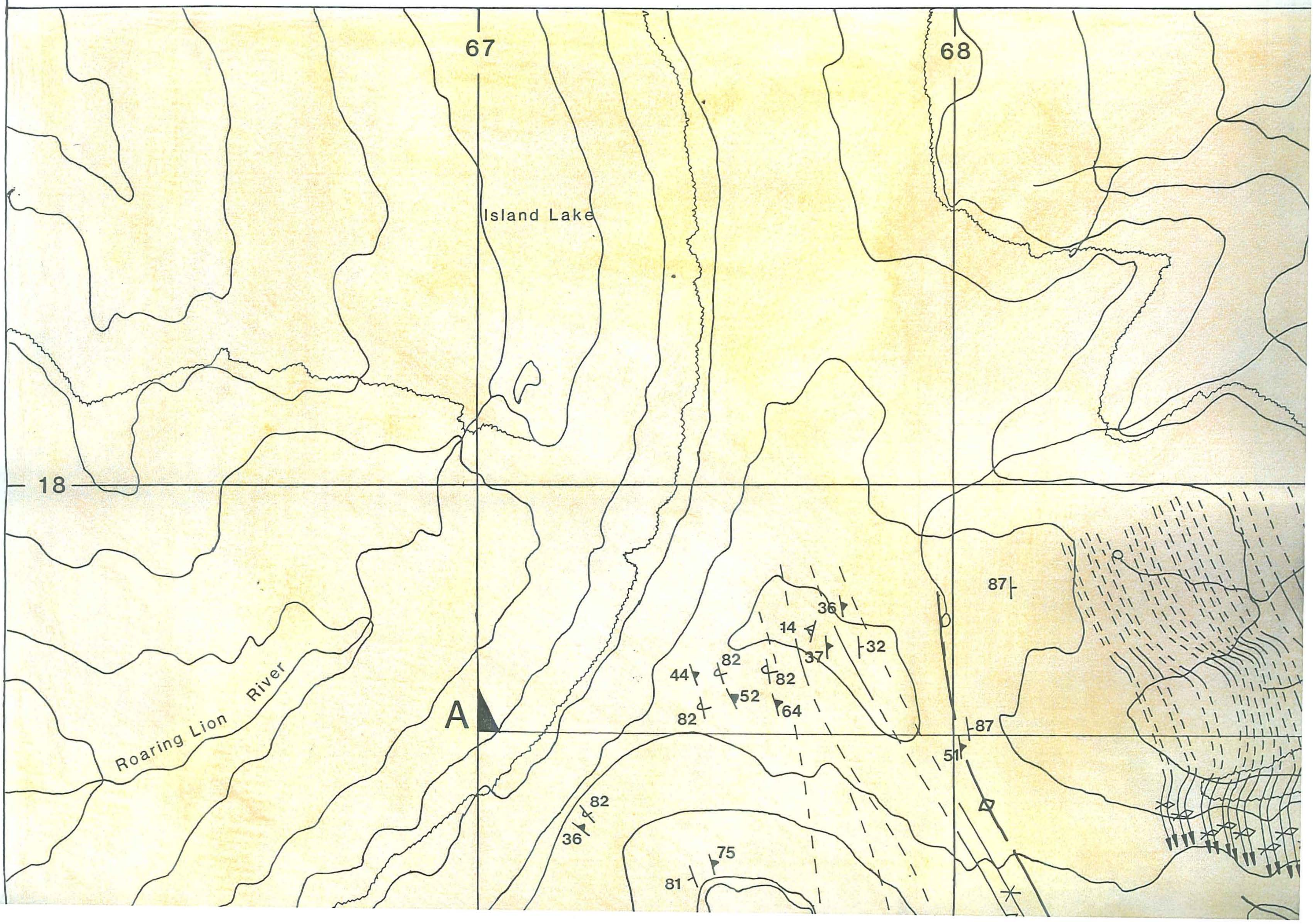
GEOLOGY OF THE UPPER (



OGICAL SYMBOLS

efined at outcrop

ot defined at outcrop

Overturned :

Concealed

Inferred

Thrust :

Plunging

Overned

500m 750m 1000m

Scale 1:10 000

REFERENCE

Huts

Trig

Track

Rivers

Bushline

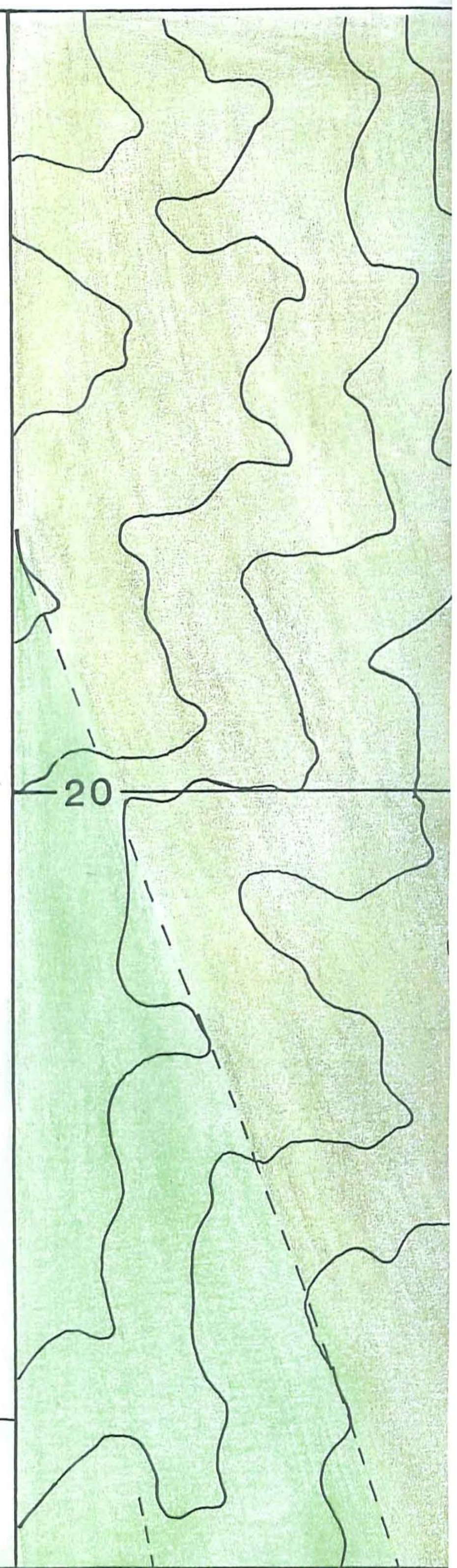
Contour Interval 100m

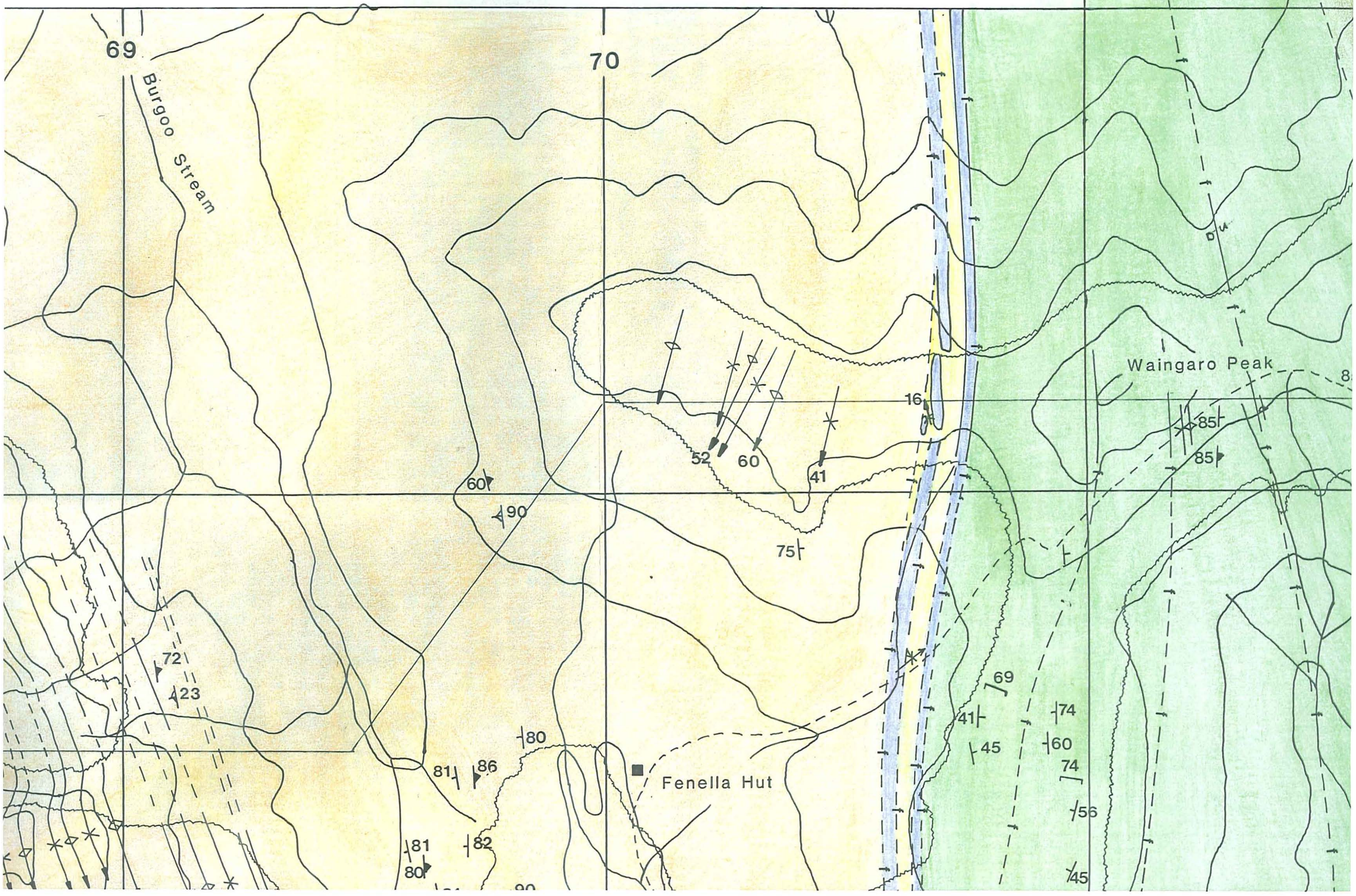
GRID NORTH

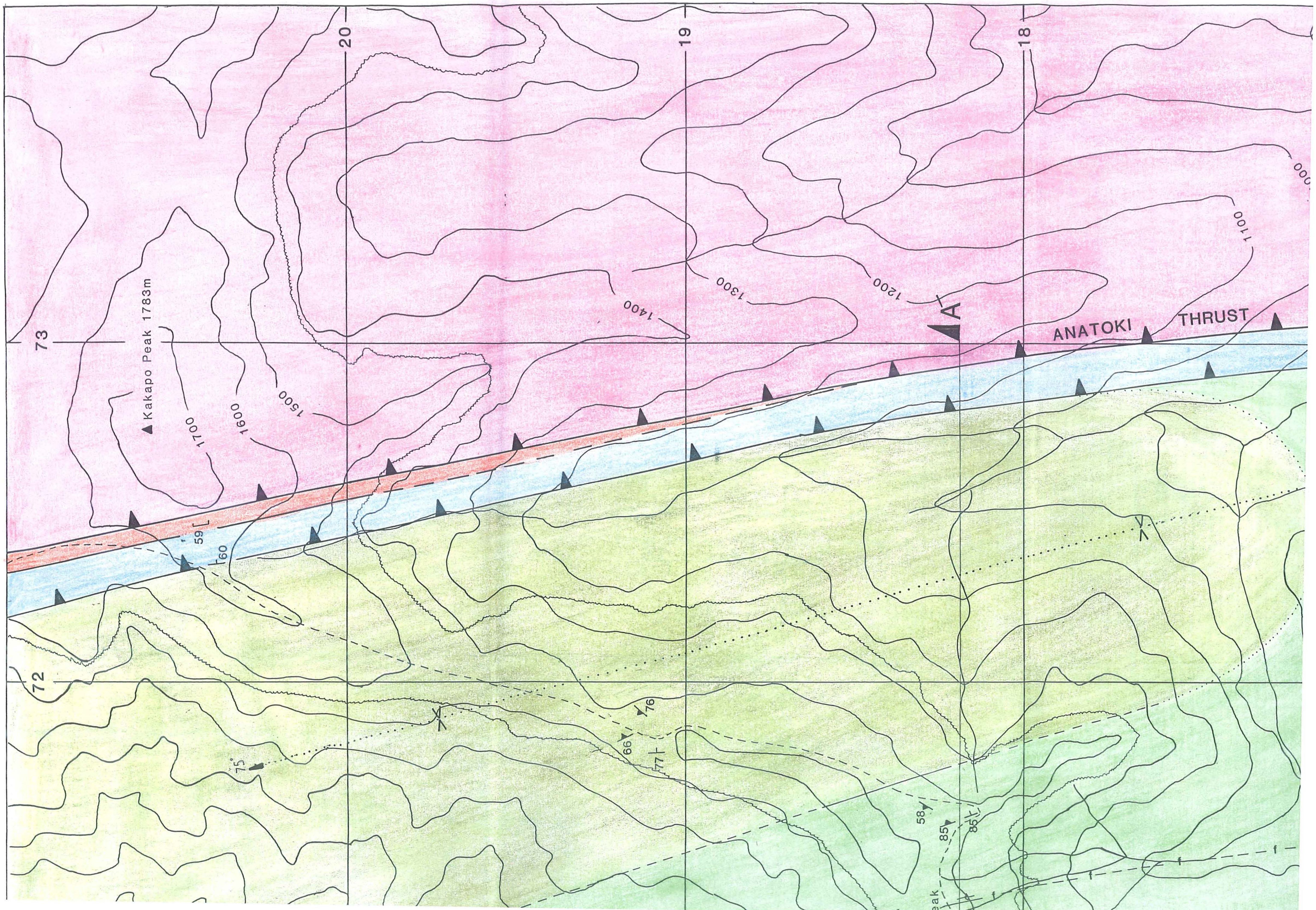
$21\frac{1}{2}°$

MAG. NORTH

COBB VALLEY AREA






ANATOKI THRUST
Kakapo Peak 1783m
A
20
19
18
73
72
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1600
1500
1400
1300
1200
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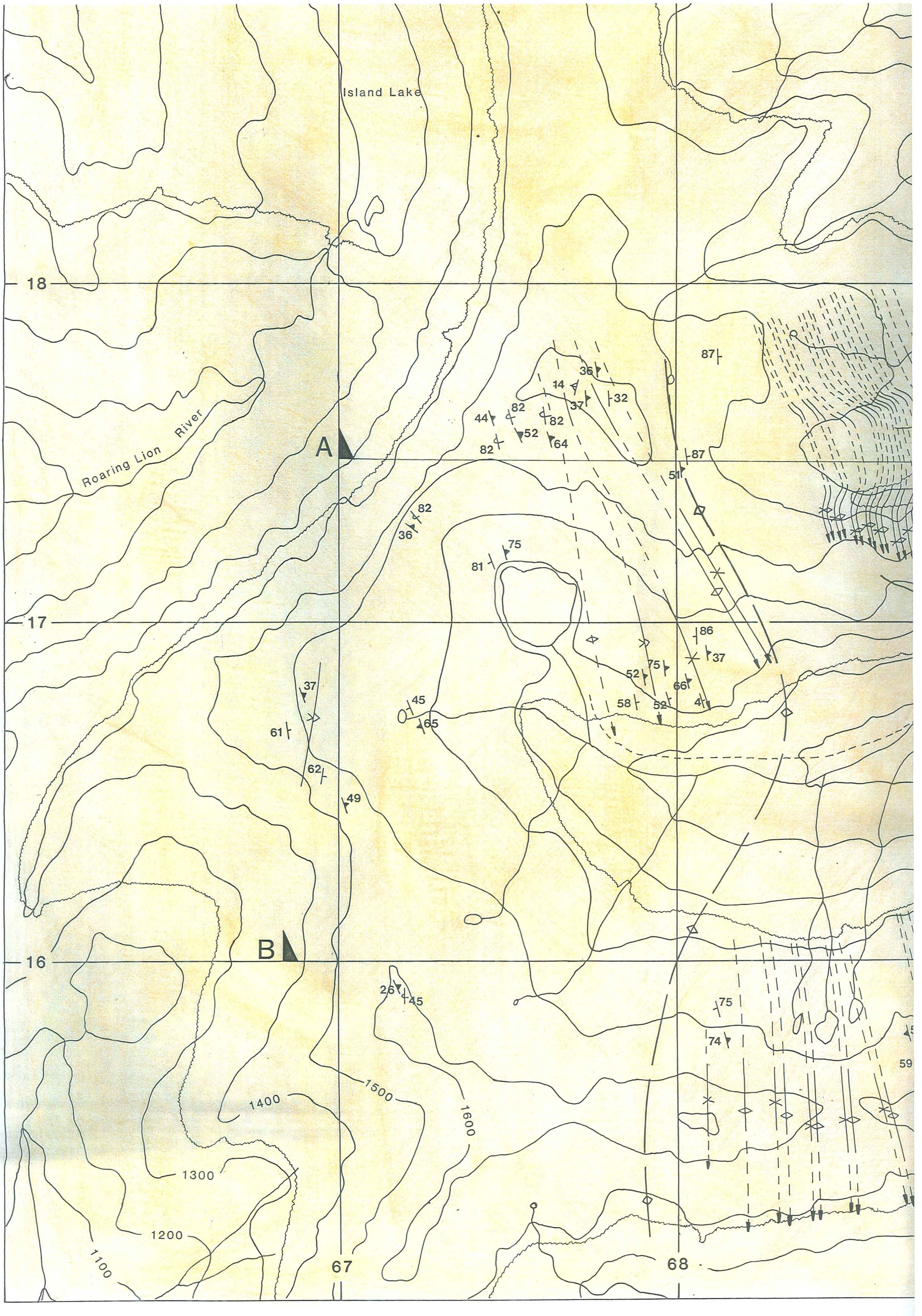
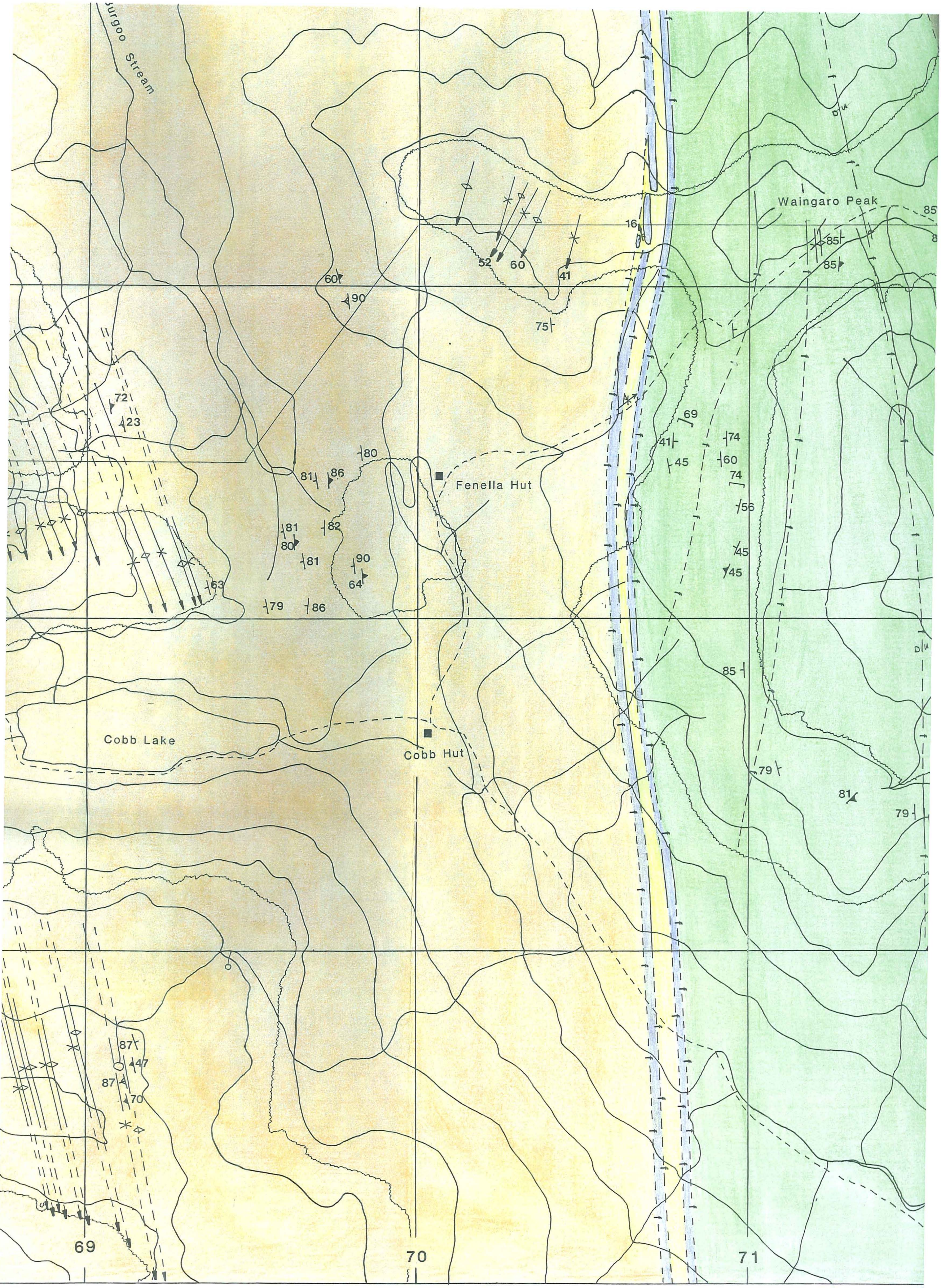
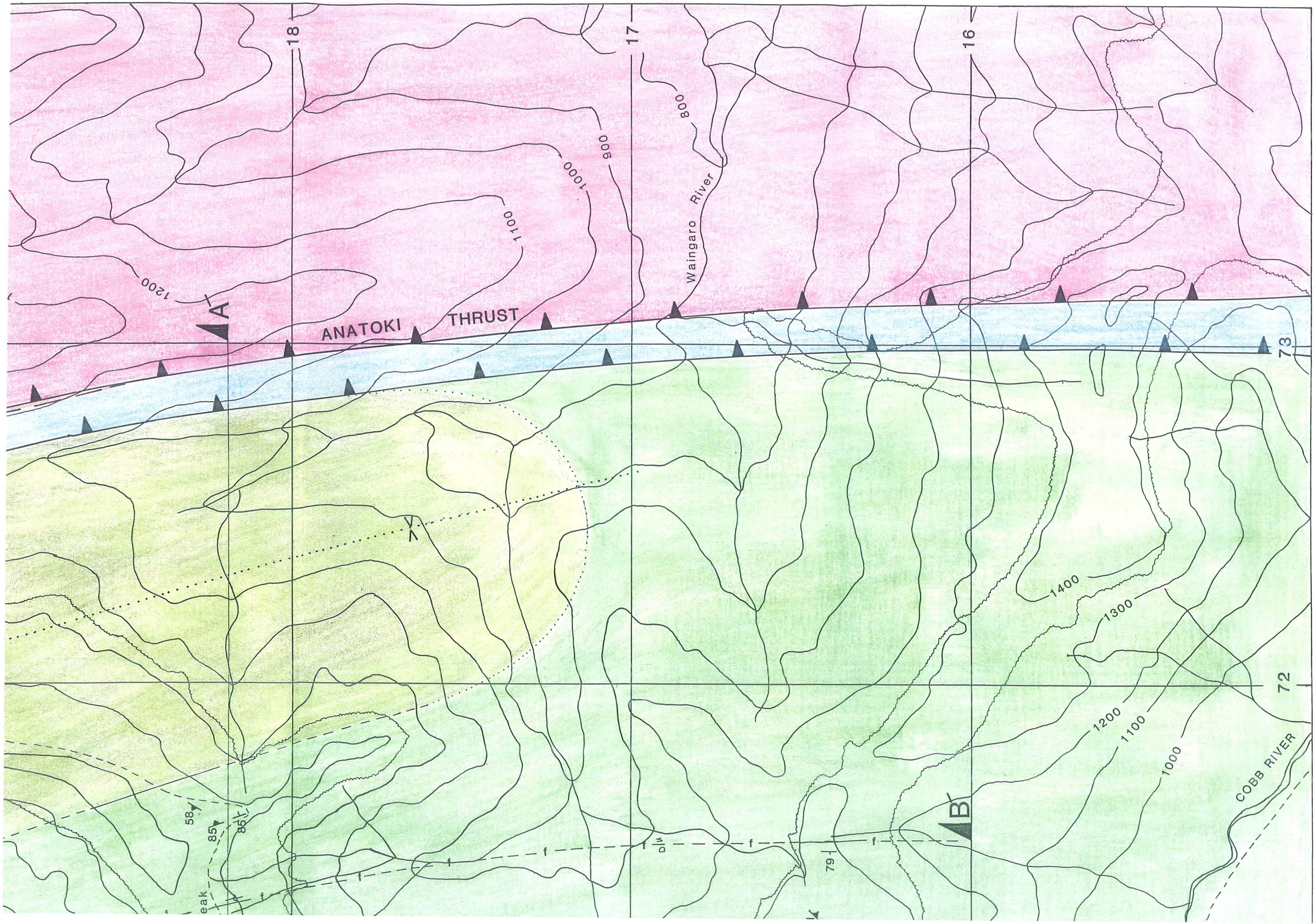
77
75
58
85
85



Island Lake
Roaring Lion River
A
B
18
17
16
67
68
1100
1200
1300
1400
1500
1600


urgoo Stream
Waingaro Peak
Fenella Hut
Cobb Lake
Cobb Hut
69
70
71


18
17
16
73
72
ANATOKI THRUST
Waingaro River
800
900
1000
1100
1200
A
B
1400
1300
1200
1100
1000
COBB RIVER
58
85
85
79
f